ENGINEERING ELECTRICITY

HUDSON

THIRD EDITION

ENGINEERING ELECTRICITY

HUDSON

ENGINEERING ELECTRICITY

ENGINEERING ELECTRICITY

BY

RALPH G. HUDSON, S. B.

Professor of Electrical Engineering

In Charge of the Courses in
General Science and General Engineering
at the
Massachusetts Institute of Technology

THIRD EDITION

NEW YORK
JOHN WILEY & SONS, INC.
LONDON: CHAPMAN & HALL, LIMITED

THIRD EDITION

Second Printing, October, 1944

PRINTED IN THE UNITED STATES OF AMERICA

PREFACE TO THE THIRD EDITION

This book was written primarily for technical students not specializing in electrical engineering but may also serve as an introductory textbook for electrical engineering students. At the Massachusetts Institute of Technology the subject is required for students registered in metallurgy, general engineering, chemical engineering, mineral resources (option in geology), naval architecture and marine engineering, marine transportation, business and engineering administration, aeronautical engineering, and building engineering and construction. It is sometimes elected by students registered in chemistry and in physics.

The first obvious pedagogical question that arises is whether a different training should be offered to each of the professions listed above. The nationwide answer has been practically unanimous that, from every viewpoint, a single course with a broad objective should be adopted. This solution, however, predicates a course content and a method of teaching which will allow the registrants in each faction to study and think in terms of their own field of activity. This may best be accomplished by meeting each group, so far as possible, in a class discussion rather than in a general lecture to the whole body, and by selecting appropriate laboratory exercises for each group.

With this objective in mind the text has been written to include an outline of the fundamental principles and applications of electricity and magnetism most frequently encountered in engineering practice. An outline text also provides the individually minded teacher with the opportunity, without restrictions, of extending the subject in those directions in which he believes the greatest emphasis should be given.

The extensive and increasing use of thermionic and photoelectric emission in modern electrical apparatus has introduced another difficult problem in the teaching of non-electrical students. A chapter on electronic theory and applications has been included

in the third edition; its study and discussion should give the student better understanding of the various electronic devices with which he may come in contact. In the limited time available it is not to be expected that the student will be able to design such devices. The best that may be expected is that he will be able to apply and operate existing devices.

The photographic reproductions of electrical apparatus appearing throughout the text were generously supplied by the General Electric Company, the Westinghouse Electric and Manufacturing Company, the Weston Electrical Instrument Company, the Leeds and Northrup Company, the Simplex Wire and Cable Company, the Okonite Company, the International Telephone Development Co., Inc., the Locke Insulator Corporation, the Ohio Brass Company, and the American Bridge Company.

RALPH G. HUDSON.

CAMBRIDGE, MASS.
September, 1941

All names of apparatus mentioned in this text which are capitalized and quoted are trade names.

TABLE OF CONTENTS

in the third edition; its study and discussion should give the student better understanding of the various electronic devices with which he may come in contact. In the limited time available it is not to be expected that the student will be able to design such devices. The best that may be expected is that he will be able to apply and operate existing devices.

The photographic reproductions of electrical apparatus appearing throughout the text were generously supplied by the General Electric Company, the Westinghouse Electric and Manufacturing Company, the Weston Electrical Instrument Company, the Leeds and Northrup Company, the Simplex Wire and Cable Company, the Okonite Company, the International Telephone Development Co., Inc., the Locke Insulator Corporation, the Ohio Brass Company, and the American Bridge Company.

RALPH G. HUDSON.

CAMBRIDGE, MASS.
September, 1941

All names of apparatus mentioned in this text which are capitalized and quoted are trade names.

TABLE OF CONTENTS

CHAPTER I

DIRECT-CURRENT CIRCUITS

Electric Current. The economic value of electric energy is due principally to the possibility of transmitting this form of energy in large quantities over great distances without considerable loss. The propagation of electric energy through space along a wire is accompanied by certain manifestations located within the wire or in the surrounding space. These manifestations associated with the propagation of electric energy are ascribed to a flow of electricity through the wire and this flow of electricity is called an electric current.

Modern Concept of an Electric Current. Matter is an aggregate of small electric charges; principally protons (positive charges), electrons (negative charges), and neutrons (each containing one proton combined with one electron). All substances contain varying amounts of free electrons which, without extraneous forces acting upon them, move about at random like the molecules in a gas.

The electron carries a charge of 4.80×10^{-10} statcoulomb and has a mass (at rest) of 9.04×10^{-28} gram. The size of an electron is questionable but is probably not more than 10^{-13} centimeter in diameter. The proton carries the same charge as the electron but has a mass about 1840 times that of the electron.

If the free electrons in any substance are acted upon by a force of external origin they will be given a drift velocity and a stream of electrons will move slowly through the substance. In a wire carrying a current of one ampere (defined below), 6.29×10^{18} electrons will pass a given cross section of the wire in one second. In a copper wire 0.04 inch in diameter (about No. 18 A.W.G.) carrying a current of one ampere a free electron would move a distance of one mile in about 231 days. This slow motion of free electrons in any part of a wire propagates a wave of action throughout the entire wire almost at the velocity of light.

CHAPTER I

DIRECT-CURRENT CIRCUITS

Electric Current. The economic value of electric energy is due principally to the possibility of transmitting this form of energy in large quantities over great distances without considerable loss. The propagation of electric energy through space along a wire is accompanied by certain manifestations located within the wire or in the surrounding space. These manifestations associated with the propagation of electric energy are ascribed to a flow of electricity through the wire and this flow of electricity is called an electric current.

Modern Concept of an Electric Current. Matter is an aggregate of small electric charges; principally protons (positive charges), electrons (negative charges), and neutrons (each containing one proton combined with one electron). All substances contain varying amounts of free electrons which, without extraneous forces acting upon them, move about at random like the molecules in a gas.

The electron carries a charge of 4.80×10^{-10} statcoulomb and has a mass (at rest) of 9.04×10^{-28} gram. The size of an electron is questionable but is probably not more than 10^{-13} centimeter in diameter. The proton carries the same charge as the electron but has a mass about 1840 times that of the electron.

If the free electrons in any substance are acted upon by a force of external origin they will be given a drift velocity and a stream of electrons will move slowly through the substance. In a wire carrying a current of one ampere (defined below), 6.29×10^{18} electrons will pass a given cross section of the wire in one second. In a copper wire 0.04 inch in diameter (about No. 18 A.W.G.) carrying a current of one ampere a free electron would move a distance of one mile in about 231 days. This slow motion of free electrons in any part of a wire propagates a wave of action throughout the entire wire almost at the velocity of light.

The Effects of an Electric Current. The principal effects of an electric current are the thermal, chemical, magnetic, and force effects. The thermal effect is manifested by the heating of the conducting material, by a high temperature arc between the terminals of a gap in the circuit, and by the heating or cooling of the junction between different metals conducting an electric current; the chemical effect by the chemical reaction associated with the flow of current through certain materials, chiefly liquids; the magnetic effect by the associated magnetic energy stored in the space surrounding a current; the force effect by the force exerted upon a current when placed in space containing magnetic energy.

In an automobile, for example, the thermal effect is used to produce sparks in the spark plug gaps within the cylinders, and to heat the filaments of incandescent lamps; the chemical effect is used when the storage battery is charged and discharged; the magnetic effect is used in the storage and discharge of magnetic energy in the ignition system, and in the excitation of the charging generator and starting motor fields; the force effect in the starting motor, and in reaction in the charging generator.

Definition of the Ampere. The magnitude of an electric current may be defined arbitrarily in terms of any one of its effects. Though the force effect was first chosen for such definition the chemical effect proved more convenient and the unit of current,

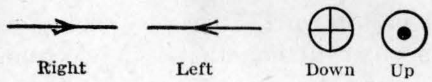


FIG. 1

the ampere, is now defined as that strength of current which will deposit 1.11800 milligrams of silver per second from an aqueous solution of pure silver nitrate (see Fig. 85 on page 84). The direction of the current is assumed to be toward the surface on which the silver is deposited. The symbol for current is I and its direction is indicated by the horizontal or vertical projection of an arrow as shown in Fig. 1.

Energy Conversion Associated with an Electric Current. The flow of an electric current through any part of an electric circuit

is accompanied by a continuous conversion of energy from one form into another. The nature of the conversion in any part depends upon its material structure, the constancy of the current, the lateral motion of the current in magnetic space, and the fixity of the magnetic energy in the surrounding space. The flow of an electric current in all substances is accompanied by a conversion of electric into thermal energy and, in certain dissimilar metals in contact, by a conversion of electric to thermal energy or the reverse. In certain materials, especially liquids, an additional conversion from electric to chemical energy or the reverse takes place. A variable current is accompanied by a conversion from electric to magnetic energy or the reverse, and lateral motion of a current in magnetic space may be accompanied by a conversion of electric into mechanical energy or the reverse.

Definition of Electromotive Force. Each case in which the energy conversion is stated to be reversible may be utilized either as a source of electric energy or as a receiver of electric energy. Any device possessing the property of reversible conversion is called a reversible converter. The rate of reversible conversion in most reversible converters is directly proportional to the current. The rate of reversible conversion, or the reversible power, per unit current is called the electromotive force of the converter. When the power is measured in watts and the current in amperes the electromotive force is measured in volts. Electromotive force is commonly abbreviated " emf " and is given the symbol E. Hence the emf of any device in which a current of I amperes is accompanied by a reversible conversion at a rate of P watts is given by

1 $$E = \frac{P}{I} \text{ volts.}$$

The direction of the emf in any reversible converter is assumed to be in the direction of the current if the converter is a source of electric power and in the opposite direction to the current if the converter is a receiver of electric power. A reversible converter of constant emf is represented by the symbol and it is assumed that the emf acts within such a converter from the short line to the long line.

Definition of Resistance. The order of the conversion of energy in many substances, especially solids, is independent of the direction of the current (electric energy being converted into thermal energy with either direction of the current) and the rate of conversion in such substances is proportional to the square of the current. In an irreversible converter the rate of conversion per unit of current is therefore a variable but the ratio of the rate of conversion to the current squared is a constant and is called the resistance of the irreversible converter. When the power is measured in watts and the current in amperes the resistance is measured in ohms. The symbol for resistance is R and an irreversible converter is represented by the symbol —ww—. Hence the resistance of any device in which electric energy is converted into thermal energy with either direction of the current at a rate of P watts when the current is I amperes is given by

2 $$R = \frac{P}{I^2} \text{ ohms.}$$

The resistance of any device may also be expressed in microhms (one microhm equals one-millionth of an ohm), or in megohms (one megohm equals one million ohms).

Rate of Energy Conversion or Power. The reversible power converted in any device of emf E volts when conducting a current of I amperes, from 1, is given by

3 $$P = EI \text{ watts.}$$

Positive power indicates conversion into electric power and negative power conversion from electric power.

The irreversible power converted in any device of resistance R ohms when conducting a current of I amperes, from 2, is given by

4 $$P = I^2R \text{ watts.}$$

This power is negative since electric power is always converted into thermal power in an irreversible converter.

Definition of Potential or Voltage. The electric power delivered from any part of an electric circuit confined between two points a and b (Fig. 2), from 3 and 4, is given by

5 $$P_{ab} = +EI - I^2R \text{ watts.}$$

The power delivered per ampere from any part of an electric circuit confined between two points a and b is called the potential or voltage between the two points. Dividing 5 by I, the potential or voltage (V) between the two points a and b in Fig. 2 is then given by

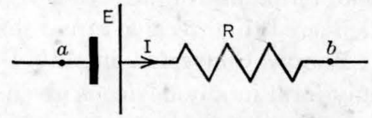


FIG. 2

6 $$V_{ab} = +E - IR \text{ volts,}$$

where E is positive if directed toward b and I is positive if flowing toward b. A positive value of V_{ab} indicates a potential rise toward b and a negative value a potential drop toward b.

The power delivered from any part of a circuit, by definition of V, is given by

7 $$P = VI \text{ watts.}$$

In 7, V is positive for a potential rise in the direction of the current and is negative for a potential drop in the direction of the current. Positive power indicates electric power delivered from, and negative power, electric power delivered to, the part of the circuit under consideration.

Comparative Meaning of Emf and Potential. The emf in any part of an electric circuit indicates the rate of reversible energy conversion per ampere in that part of the circuit either from electric energy to some other form or the reverse, depending upon the relative direction of the current and the emf. The magnitude or the direction of the emf does not depend upon the magnitude or the direction of the steady current unless the current changes the physical state of the converter. The potential or voltage between two points in any circuit indicates the rate of energy per ampere delivered or received between the two points in any form. Potentials or voltages are the consequences of the action of emf's upon circuits. The magnitude or the direction of the potential between two points may and usually does depend upon the magnitude and direction of the current flowing between the two points. No current can be established in any circuit which contains no emf but current may flow in a circuit in which the potential between any two points is zero. The electromotive force of any device indicates

the power converted per ampere within that device exclusive of the power converted into heat in the device due to the passage of current through its material substance. The potential between the terminals of any device indicates the power per ampere delivered to or received from the device in any form.

Energy Converted in Any Device. The energy converted to any form in any device is given by

8 $$W = \frac{VIh}{1000} \text{ kilowatthours,}$$

where V is the potential between the terminals of the device, I is the current flowing through the device, and h is the number of hours that the device is electrically connected.

The energy of reversible form that is converted from electric energy to any other form or the reverse depending upon the direction of the current in any device is given by

9 $$W = \frac{EIh}{1000} \text{ kilowatthours,}$$

where E is the emf of the device. (I and h are described under 8.)

The energy converted into heat in any device with either direction of the current is given by

10 $$W = \frac{I^2Rh}{1000} \text{ kilowatthours,}$$

where R is the resistance of the device. (I and h are described under 8.)

Series and Parallel Connections. When the various parts of an electric circuit are connected end to end successively, as shown in Fig. 3, it is called a series connection. The current throughout a series connection is the same in each part. If some of the parts of a circuit are connected end to end jointly, as shown in Fig. 4, it is called a parallel connection. The potential between the terminals of each part of a parallel connection is the same for each part. It should not be assumed that all connections are either series or parallel. In Fig. 5 or Fig. 6, for example, none of the parts is connected in series or in parallel.

Properties of the Series Connection. The resultant emf (E_{ad}) in a stated direction in a series connection (see Fig. 7) equals the algebraic sum of its constituent emf's, an emf acting in the stated

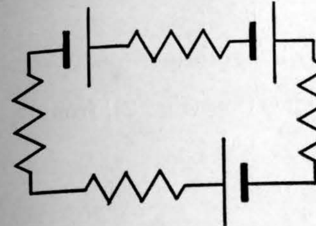


FIG. 3

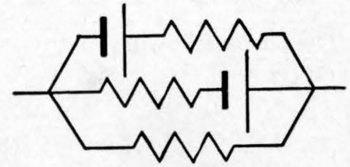


FIG. 4

direction being positive and in the opposite direction, negative. Hence

11 $$E_{ad} = E_1 + E_2 + E_3 \text{ volts.}$$

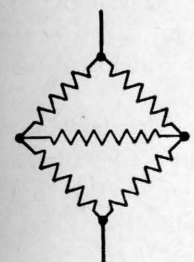


FIG. 5

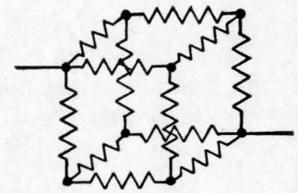


FIG. 6

If $E_1 = +20$ volts, $E_2 = -10$ volts, and $E_3 = +4$ volts, in Fig. 7 $E_{ad} = +20 - 10 + 4 = +14$ volts acting from a to d.

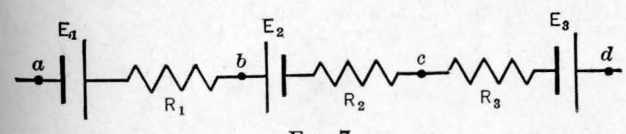


FIG. 7

The resultant resistance (R_{ad}) of a series connection (see Fig. 7) equals the arithmetic sum of its constituent resistances. Hence

12 $$R_{ad} = R_1 + R_2 + R_3 \text{ ohms.}$$

The potential rise in a stated direction between the ends of a series connection equals the algebraic sum of the potentials between the ends of its constituent parts, a potential rise in the stated direction being positive and a potential drop negative.

Hence, in Fig. 7,

13 $$V_{ad} = +V_{ab} + V_{bc} + V_{cd} \text{ volts.}$$

The current flowing in any series connection (Fig. 2), from 6, is given by

14 $$I = \frac{+E - V_{ab}}{R} \text{ amperes.}$$

All quantities represented in 14 apply only to a single series connection located between a and b. E is the resultant emf of the connection between a and b, V_{ab} is the potential between a and b, R is the resultant resistance of the connection between a and b, and I is the current flowing from a to b. The convention of signs is the same as that described under 6. In a continuous series connection, called a series circuit (see Fig. 3), a and b are identical points and V_{ab} equals zero.

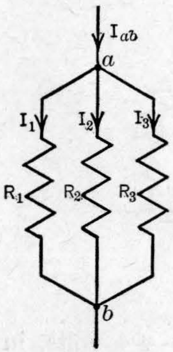


FIG. 8

Properties of the Parallel Connection. In any parallel connection the sum of the currents flowing toward any junction equals the sum of the currents flowing away from that junction. In Fig. 8, it may then be stated that

15 $$I_{ab} = I_1 + I_2 + I_3 \text{ amperes.}$$

Parallel Connections Containing No Emf's. If no part of a parallel connection contains an emf it follows, from 14, that in Fig. 8

$$I_{ab} = \frac{V_{ab}}{R_{ab}}, \quad I_1 = \frac{V_{ab}}{R_1}, \quad I_2 = \frac{V_{ab}}{R_2}, \quad \text{and} \quad I_3 = \frac{V_{ab}}{R_3}.$$

Then, from 15,

$$\frac{V_{ab}}{R_{ab}} = \frac{V_{ab}}{R_1} + \frac{V_{ab}}{R_2} + \frac{V_{ab}}{R_3} \quad \text{and}$$

16 $$\frac{1}{R_{ab}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

where R_{ab} is the equivalent resistance of a parallel connection containing no emf. When the parallel connection contains only two parts, $R_{ab} = \dfrac{R_1R_2}{R_1 + R_2}$ and when n parts, each of resistance R, are connected in parallel, $R_{ab} = \dfrac{R}{n}$. From 6 it also follows that in Fig. 8

17 $$I_1R_1 = I_2R_2 = I_3R_3 = I_{ab}R_{ab}.$$

In any circuit containing parallel connections without emf's the circuit as a whole may be converted into a simple series circuit for the purpose of calculation by substituting for each of its parallel connections the equivalent resistance given by 16.

Parallel Connections Containing Emf's. When two or more parts of any circuit are not connected in series and contain emf's, the resultant emf or the resultant resistance of the circuit cannot be calculated and the determination of the magnitude and direction of the current in each part involves the solution of two or more simultaneous equations based upon 6 and 15.

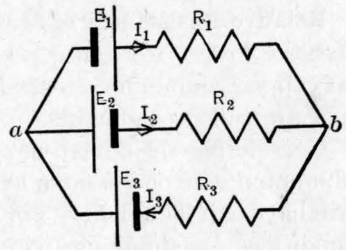


FIG. 9

Example. The currents flowing in the various parts of the circuit shown in Fig. 9 are indicated arbitrarily in magnitude and direction by symbols and arrows. Then between the two points a and b, from 6,

$$(1) \quad +E_1 - I_1R_1 = -E_2 - I_2R_2$$

$$(2) \quad -E_2 - I_2R_2 = -E_3 + I_3R_3$$

and from 15,

$$(3) \quad I_1 + I_2 = I_3.$$

The magnitude and actual direction of each of the currents may be determined by solving the three simultaneous equations, a positive value of current in any case indicating that the direction assumed in the figure is correct and a negative value indicating a direction opposite to that in the figure.

The same method applies to connections which are neither series nor parallel. In Fig. 10 which contains the non-series parallel connection of Fig. 5, given E, R_1, R_2, R_3, R_4, and R_5 (resistance of the battery and its connections assumed negligible), then from 6 between a and b with the assumed directions of currents

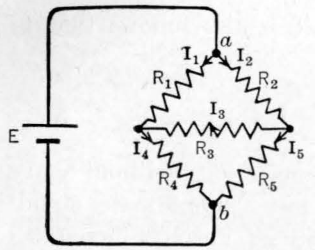


FIG. 10

(1) $-E = -I_1R_1 - I_4R_4$

(2) $-E = -I_2R_2 - I_5R_5$

(3) $-E = -I_2R_2 - I_3R_3 - I_4R_4$

(4) $I_1 + I_3 = I_4$

(5) $I_2 = I_3 + I_5$

Solving the five simultaneous equations gives the magnitude and direction of each current.

Relative Resistances of Materials. Among the elements, silver has the lowest resistance per unit volume. Other metals, such as copper, aluminum, iron, also possess relatively low resistance and are called conductors.

Considering their relative specific gravities and resistivities an aluminum wire of the same length and resistance as a copper wire will have half its weight. For conduction purposes under identical conditions an aluminum wire will therefore cost the same as a copper wire when the aluminum wire costs twice as much per pound. Lighter poles or towers may be used with the aluminum wire because it weighs half as much as the equivalent copper wire. Aluminum wires, being larger than the equivalent copper wires (unless the latter are hollow), will operate with less corona loss (explained later) but will collect more sleet out of doors. The larger wires will furthermore take more room, which is particularly undesirable indoors, in machinery, or in underground conduits. The low tensile strength of aluminum is easily compensated for by using high tensile strength steel for the inner strands of a stranded wire. Copper is preferable when much soldering is to be done because aluminum is difficult to solder.

The wire used for heating elements in various types of electric heaters is subjected to a high rate of oxidation by reason of its high temperature. The rate of oxidation is materially reduced by

using an alloy containing copper, nickel, and chromium. Incandescent lamp filaments operated at very high temperatures are usually made of tungsten. Carbon filaments have a higher melting point but lose their substance rapidly by reason of a higher vapor pressure than that possessed by tungsten.

Various materials, such as glass, porcelain, slate, rubber, dry oil, possess relatively high resistance and are called insulators. All materials conduct current, however, and the distinction between conductors and insulators is made only to express their relative resistances per unit volume. The ratio of the resistance per unit volume of dry mineral oil to copper is 10^{22} to 1.

The American Wire Gage. The length of electric wires is usually measured in feet, the diameter in mils (1 mil equals 0.001 inch) and the area in circular mils (area in circular mils equals the square of the diameter in mils). Wires are drawn for general use in various sizes represented by the American Wire Gage in which the consecutive sizes differ in area by approximately 26 per cent. A copper wire table giving the constants of wires suitable for light and power circuits will be found on page 219.

Resistance Calculations. The resistance of any wire of uniform cross section is proportional to its length and inversely proportional to its cross-sectional area. Given the resistance (R_1), length (l_1), and area (A_1) or weight (W_1) of any wire, the resistance of any other wire of the same material of length (l_2), area (A_2) or weight (W_2) is determined by

18 $$\frac{R_1}{R_2} = \frac{l_1A_2}{l_2A_1} = \frac{l_1^2W_2}{l_2^2W_1}.$$

Any units of length, area or weight may be employed, provided the same units are used for both wires. If the given wire is one foot long and one mil in diameter it is called a mil-foot of wire and its resistance is called the resistivity (ρ) in ohms per mil-foot of the material. Given the resistivity (ρ) of any material per mil-foot the resistance of any wire of the same material l feet in length and A circular mils in cross-sectional area is given by

19 $$R = \frac{\rho l}{A} \text{ ohms.}$$

The resistivity of a material may also be expressed in microhms

per centimeter cube, megohms per centimeter cube or ohms per meter-gram.

The resistivity of various materials in microhms per centimeter cube and megohms per centimeter cube is given on page 222.

Variation of Resistance with Temperature. The resistance of all materials changes with the temperature and is assumed to be zero for all materials at zero degrees absolute. The resistance (R_2) of any material at t_2 C which has a resistance of R_1 ohms at t_1 C is given by

20 $$R_2 = R_1 [1 + \alpha_1(t_2 - t_1)] \text{ ohms},$$

where α_1 is the resistance-temperature coefficient of the material at t_1 C. Values of α for various materials are given on page 222. The resistance-temperature coefficient of annealed 100 per cent conductivity copper at any temperature is given by

21 $$\alpha_t = \frac{1}{234.5 + t}.$$

The temperature (t_2) of a material of R_2 ohms resistance which has a resistance of R_1 ohms and a resistance-temperature coefficient of α_1 at t_1 C, from 20, is given by

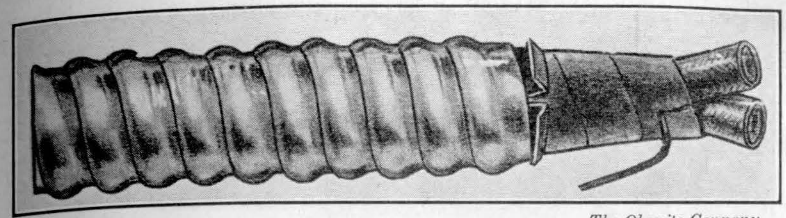
22 $$t_2 = \left[\frac{R_2 - R_1}{\alpha_1 R_1} + t_1\right] \text{ degrees.}$$

For annealed 100 per cent conductivity copper

23 $$t_2 = \left[\left(\frac{R_2 - R_1}{R_1}\right)(234.5 + t_1) + t_1\right] \text{ degrees.}$$

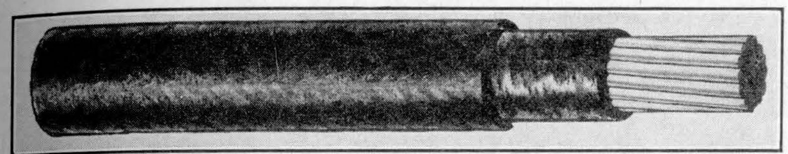
It will be noted that Formula 22 or 23 furnishes an accurate method for the measurement of temperature. A wire of high melting point with R_1 and α_1 (Formula 22) known at t_1 may be placed in a furnace. After it is heated to the temperature of the furnace, R_2 can be measured and t_2 can be calculated to a high degree of accuracy.

Insulation of Wires. Transmission line wires are usually bare and are supported by glass, porcelain or composition insulators. Types of insulation for interior wiring approved by the National Electrical Code are shown on page 15. The carrying capacity of



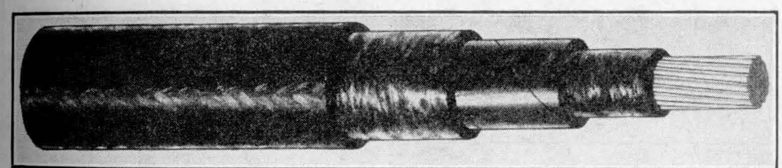
The Okonite Company

Armored Cable.



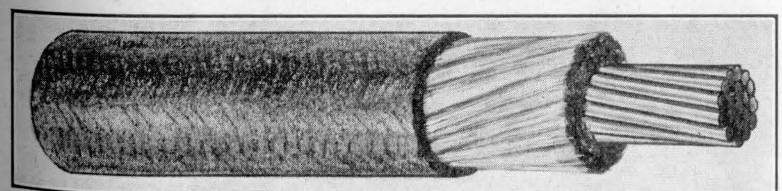
The Okonite Company

All Asbestos Insulation.



The Okonite Company

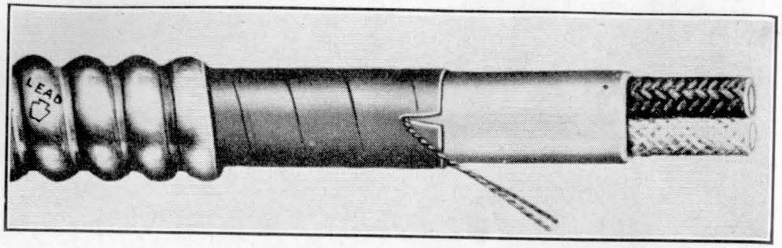
Asbestos and Varnished Cambric Insulation.



The Okonite Company

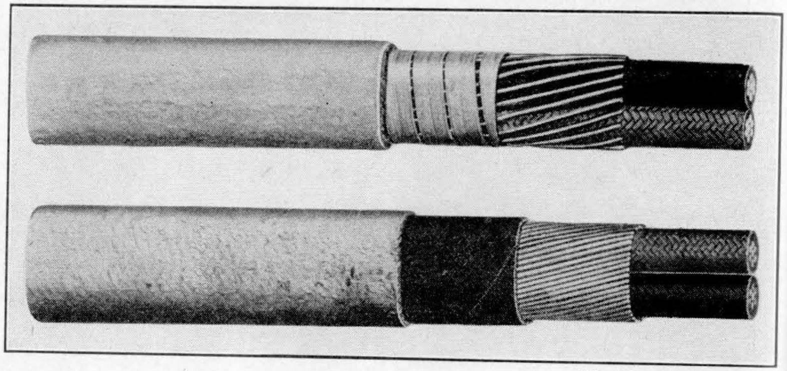
All Glass Insulation.

insulated wires or the maximum current that insulated wires may carry continuously without overheating and injuring the insulation



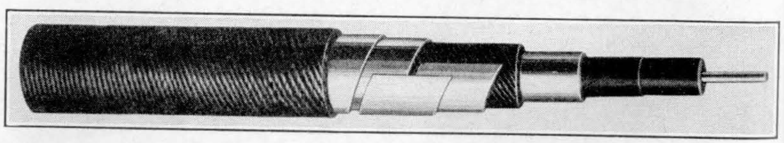
The Okonite Company

Armored Cable with Lead-covered Conductors.



The Okonite Company

Overhead Service Entrance Cables, with Bare Neutral Conductor.



The Okonite Company

Underground Parkway Cable with Lead Sheath and Steel Tape Armor.

depends upon the nature of the insulating material. The values recommended for insulated copper and aluminum wires by the National Board of Fire Underwriters are given on pages 220 and 221.

INSULATION TABLE FOR INTERIOR WIRING

Name	Type or Material	Letter	Max. Operating temp.	Application
Rubber	Code grade	R	50 C	General use
	Performance grade	RP	60 C	
	Heat-resistant	RH	75 C	
	Moisture-resistant	RW	50 C	
	Small diam. bldg. wire, heat-resistant	RHT	75 C	
	Small diam. bldg. wire, performance	RPT	60 C	
	Fibrous covering	RU	60 C	
	Synthetic	SN	60 C	
Varnished cambric	Spiral strips	V	85 C	Dry location only unless lead covered. Usually not smaller than No. 6
Asbestos varnished cambric	Braid of asbestos over above strips	AVB	90 C	AVA and AVB, dry location only
		AVA	110 C	AVL, general use
		AVL		
Asbestos	Braid	A	200 C	Connections (in conduit) to or within apparatus
Impregnated asbestos	Imp. with bitumen	AI	125 C	
Paper	Spiral strips	—	85 C	Lead-covered and underground
Slow-burning	Fireproofed cotton braid	SB	90 C	Dry location where ambient temp. exceeds 85 C
Slow-burning weatherproof	Above overlaid with cotton braid imp. with bitumen	SBW		
Weatherproof	Cotton braid imp. with bitumen	WP	80 C	Exterior wiring; interior only by special permission

Two-wire Transmission Line Calculations. The principles stated on the previous pages may be applied to the two-wire transmission line (Fig. 11) as follows:

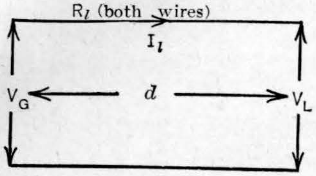


FIG. 11

V_G and V_L are the respective potentials at the generator and load ends of the line, R_l is the resistance of both line wires, d is the distance in feet from the generator to the load, I_l is the line current, and P_G and P_L are the power delivered to the line and received from the line respectively. The length (l) of the wire in a two-wire transmission line is $2\,d$. From 13,

$$V_L = V_G - I_l R_l \text{ volts.} \tag{24}$$

From 7,

$$P_G = V_G I_l \text{ watts.} \tag{25}$$

$$P_L = V_L I_l \text{ watts.} \tag{26}$$

From 7 and 4,

$$P_L = V_G I_l - I_l^2 R_l \text{ watts.} \tag{27}$$

The efficiency of transmission or the ratio of the power transmitted to the load to the power delivered to the line is given by

$$\eta = \frac{V_L I_l}{V_G I_l} = \frac{V_L}{V_G}. \tag{28}$$

From 27,

$$I_l = \frac{V_G \pm \sqrt{V_G^2 - 4\,R_l P_L}}{2\,R_l} \text{ amperes.} \tag{29}$$

From 24 and 19,

$$A = \frac{2\,\rho I_l d}{V_G - V_L} \text{ circular mils.} \tag{30}$$

From 26 and 30,

$$A = \frac{2\,\rho\, d P_L}{(V_G - V_L)\, V_L} \text{ circular mils.} \tag{31}$$

The weight of a copper wire of length, l feet, and area, A circular mils, is given by

$$G = 3.03 \times 10^{-6}\, lA \text{ pounds.} \tag{32}$$

From 32 and 31, the weight of a copper transmission line is given by

$$G = \frac{1.28 \times 10^{-4}\, P_L d^2}{(V_G - V_L)\, V_L} \text{ pounds.} \tag{33}$$

Economics of the Transmission Line. The annual cost of the energy lost in a transmission line of ρ ohms per mil-foot resistivity, l feet in length of wire, A circular mils in cross-sectional area, which conducts a steady current of I_l amperes for h hours per year, from 10, is $\dfrac{I_l^2 \rho l h c}{1000\,A}$ dollars, where c is the cost of the electric energy in dollars per kilowatthour. The annual investment charge associated with the line wires is $\dfrac{\delta l A c' p}{100}$, where δ is the weight in pounds of a mil-foot of the conducting material, c' is the cost of the wire in dollars per pound, and p is the annual (integral) percentage rate of interest on the capital invested in the line wires which will pay the annual capital interest, taxes, and depreciation on the line wires. If the first derivative (with respect to A) of the sum of the two items is equated to zero the value of A which will give a minimum annual cost of operation is given by

$$A = I_l \sqrt{\frac{\rho c h}{10\,\delta c' p}} \text{ circular mils.} \tag{34}$$

For copper the area would be $593\, I_l \sqrt{\dfrac{ch}{c'p}}$ circular mils. The result indicates that the annual operating cost associated with the wire only is a minimum when the annual cost of the lost energy equals the annual investment charge associated with the wire. This principle is called Kelvin's law.

Potential Limitations in the Two-wire System. The power lost in a transmission line, from 4, is $I_l^2 R_l$ watts. Since I_l, from 25, equals $\dfrac{P_G}{V_G}$ amperes, the power lost in a transmission line is also

given by $\dfrac{P_G^2 R_l}{V_G^2}$ watts. The power lost in the line is inversely proportional to the square of the generator potential and the generator potential should therefore be made as high as possible. The magnitude of the potential impressed between the terminals of devices receiving energy from a direct-current circuit is limited for various reasons in the case of motors to approximately 600 volts and in the case of incandescent lamps to approximately 115 volts. The operation of these devices in series is in general undesirable. Motors connected in series are difficult to insulate and their operation in series under most circumstances is unstable. The respective luminosities of incandescent lamps connected in series would vary unless the lamps were selected with care, an increase of resistance in any lamp would shorten its length of service, one lamp could not be lighted alone, the failure of one lamp would extinguish the others unless an automatic shunt was attached to each lamp, and the higher potential associated with such a connection would increase the danger of shock to those who might come in contact with the circuit.

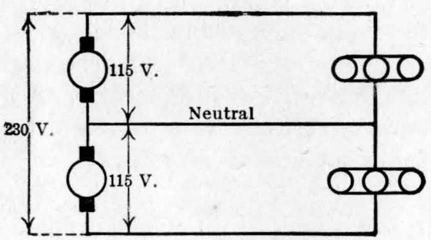


FIG. 12

The Edison Three-wire System. If the lamps in any incandescent lighting system are divided into two groups and these groups are connected to a three-wire system as shown in Fig. 12, all the disadvantages of the series connection noted above are eliminated. The current in the neutral wire will be zero if the current in each group of lamps is made the same and the efficiency of transmission will equal that of a two-wire 230-volt system. Danger of shock is removed by grounding the neutral wire so that the potential to ground from either outside wire is limited to 115

volts. A balanced three-wire system designed to replace a two-wire system (the power transmitted, length of line, power loss in the line and potential at the lamps being the same in each case) requires a weight of copper equal to 37.5 per cent of that required by the two-wire system. Although the neutral wire of a balanced system conducts no current it is usually made equal in size to either outside wire so that it may in an emergency carry as much current as either outside wire. Motors supplied from a three-wire system are usually connected between the outside wires.

Fuses should not be installed in neutral wires because an opening in the neutral wire with an unbalanced load will also unbalance the potentials at the load. Lamps and motors connected between the outside wires and the neutral wire may be burnt out and under favorable conditions fires may be started.

Practice problems with answers for Chapter I will be found on pages 227 to 234.

CHAPTER II

ELECTROMAGNETISM

The Magnetic Field. A change in the magnitude of the current flowing in any circuit is accompanied by a conversion of electric into magnetic energy or the reverse; with an increasing current electric energy is converted into magnetic energy and with a decreasing current magnetic energy is converted into electric energy. The magnetic energy thus converted from electric energy with an increasing current is distributed throughout the limitless space or field surrounding the circuit and manifests itself by a force action on an electric current or on certain materials located in that space. Any region in which such force action is manifested on an electric current or on certain materials is called a magnetic field.

Magnetic Flux. The force action associated with a magnetic field is ascribed to the reaction between the electric current placed in the field and a fictitious magnetic flux which is assumed to permeate the field of magnetic energy. The force action on certain materials placed in a magnetic field is attributed to the same reaction, the current reacted upon in this case being concealed within the atomic structure of the material. Unit magnetic flux may be visualized as a continuous tube of variable cross section and the path of such a tube may be indicated by a line which represents the axis of the tube. A single tube of magnetic flux or unit magnetic flux is called a maxwell and the axis of such a tube is called a line of flux. It should be noted that the flux permeating an area smaller than the cross section of a single tube at any point may be less than one maxwell and that the flux permeating any area will also depend upon the position of the area in space.

Magnetic Flux Density. The force acting upon a current placed in a magnetic field is proportional to the magnitude of the current, the length of the wire conducting the current, the position of the wire in the field, and the strength of the magnetic flux. The conception of magnetic flux suggests that its density be taken as a

measure of the force effect of magnetic energy. Since the force action on an electric current varies directly with the density of the magnetic flux this force action may be taken as an arbitrary measure of the magnetic flux density at any point in the field. If a wire s centimeters in length conducting a current of I amperes is placed in a magnetic flux of uniform density along the wire and the force acting normal to the wire is F dynes the magnetic flux density normal to the plane of the wire and the force is defined by

35 $$B = \frac{10\,F}{Is} \text{ gausses.}$$

Unit magnetic flux density, the gauss, equals one maxwell per square centimeter. The relative directions of the flux density (B), current (I), and force (F) are shown in Fig. 13. If the directions of the current and the force are indicated respectively by the middle finger and the thumb of the left hand the direction of

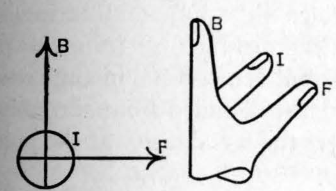


FIG. 13

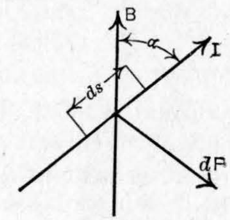


FIG. 14

the flux density normal to the plane of the current and the force is indicated by the forefinger. The direction of the magnetic flux at any point in space is normal to that plane of the current and the force in which the force acting on the current is a maximum. The flux density at a point is a maximum in the direction of the magnetic flux at the point.

Force on a Current Placed in a Magnetic Field. The force acting normal to a current element ds centimeters in length and conducting a current of I amperes placed in a magnetic field of B gausses maximum flux density when the directions of the current and the flux density differ by the angle α (Fig. 14) is given by

36 $$dF = \frac{BI\,ds \sin \alpha}{10} \text{ dynes.}$$

Flux Density Due to a Current Element. Having defined the magnitude (Formula 35) and the direction (Fig. 13) of the magnetic flux density at a point in space due to any invisible source, the magnitude and direction of the flux density due to a particular current may be determined experimentally by measuring the force exerted upon a current of definite magnitude and length placed at the point in question, the flux density being calculated by 35 and the direction determined by Fig. 13. An exploration of the magnetic field surrounding an electric current indicates that the flux density at any point (Fig. 15) is proportional to (1) the current (I) which has established the magnetic flux, (2) the length of the current path (ds), (3) the sine of the angle (α) between the extension of the line joining the point and the current element and the direction of the current, (4) the character of the medium in which the point is located (this magnetic property of the medium is called its permeability [μ]), and is inversely proportional (5) to the square of the distance (x) from the point to the current element. If the current is measured in amperes and the length of the current path and the distance from the point to the current element in centimeters the flux density at the point is given by

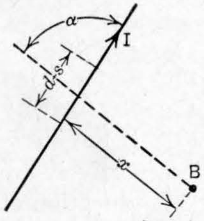


FIG. 15

37 $$dB = \frac{I\mu \sin \alpha \, ds}{10\, x^2} \text{ gausses.}$$

If a second current flowing away from the observer should be placed experimentally at B in Fig. 16, a force would be exerted on this current toward I. Then from the left-hand rule, Fig. 13, it is found that the direction of the flux density at a point due to a current element is perpendicular to the plane of the current element and the point and is clockwise in direction when the current flows away from the observer (see Fig. 16) and counterclockwise in direction when the current flows toward the observer.

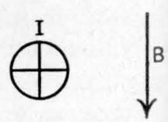


FIG. 16

Permeability of a Material. The flux density due to a current at a point located in space filled consecutively with various materials is sensibly the same for most materials but is materially increased when certain materials fill the space; notably, iron, cobalt, nickel and certain alloys of these metals with aluminum. The increased flux density resulting from the introduction of any material into the space in which the point is located is attributed to a magnetic property of the material, called its permeability. The permeability of any substance is measured by the ratio of the flux density at a point in space filled by the material in question to the flux density at the same point in air due to the same current. Hence, the permeability of any substance may be defined by the ratio,

38 $$\mu = \frac{B_{\text{material}}}{B_{\text{air}}}.$$

It should be noted that it is not the permeability of the wire or of the material in the space between the wire and the point but the permeability of the material in the space surrounding the wire and including the point that increases the flux density at the point.

The flux density in air, called the field intensity, is frequently given the symbol (H) and is measured in oersteds. The permeability of most materials is very nearly one and such materials are called non-magnetic. All materials of permeability greater than one are called paramagnetic and the permeability of such materials may be as high as 72,000 for electrolytic iron, 480 for nickel, and 270 for cobalt. Certain alloys after appropriate heat treatment possess even higher permeabilities at low flux densities. The highest value (610,000) for commercial materials is obtained with "65 permalloy" which contains 65% Ni and 35% Fe. Single crystals of pure iron and certain nickel-iron alloys have permeabilities exceeding one million. The permeability of all magnetic materials is comparatively low when placed in a magnetic field of high field intensity. When certain materials are placed in space formerly occupied by air the flux density in this space is decreased. Materials possessing this property (bismuth is the best example) are called diamagnetic and the permeability of such materials is slightly less than one.

Flux Density Due to a Current Path of Any Shape. The flux density produced at a point in space by a current path of any

length or shape may be determined in any case by integrating the flux densities at the point due to the elements of the current path. The results of such integrations of 37 are given for certain cases as follows:

Case I. Flux density at a normal distance of a centimeters from the axis and outside of a straight wire (Fig. 17) conducting I amperes and surrounded by a medium of permeability (μ).

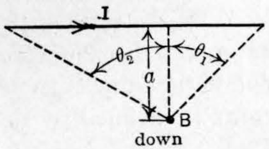


FIG. 17

39 $B = \dfrac{I\mu}{10\,a}(\sin\theta_1 + \sin\theta_2)$ gausses.

When the distance from the wire to the point is negligible compared to the length of the wire, $\sin\theta_1 + \sin\theta_2 = 2$ and $B = \dfrac{0.2\,I\mu}{a}$ gausses.

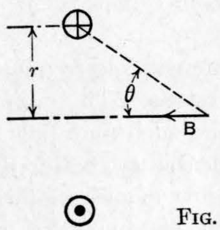


FIG. 18

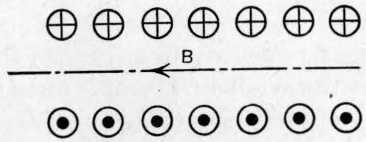


FIG. 19

Case II. Flux density on the axis of a single turn of wire (Fig. 18) r centimeters in radius conducting I amperes and surrounded by a medium of permeability (μ).

40 $$B = \frac{0.628\,I\mu\sin^3\theta}{r}\text{ gausses.}$$

Case III. Flux density on the axis near the middle of a long solenoid (Fig. 19) wound uniformly with n turns of wire per centimeter length of axis, each turn conducting I amperes and surrounded by a medium of permeability (μ).

41 $$B = 1.26\,nI\mu\text{ gausses.}$$

Case IV. Flux density at a point distant r centimeters from the axis of and within a toroidal coil (Fig. 20) of N turns conducting a current of I amperes and wound upon a toroidal core of permeability (μ).

42 $$B = \frac{0.2\,NI\mu}{r}\text{ gausses.}$$

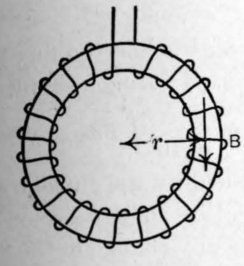


FIG. 20

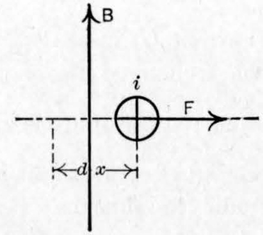


FIG. 21

Energy Converted by a Variation in the Flux Linking a Current. The force acting on a wire (Fig. 21) ds centimeters in length conducting a current of i amperes and placed in a plane normal to a magnetic flux of B gausses flux density, from 36, is given by $dF = \dfrac{Bi\,ds}{10}$ dynes. The direction of the force, from Fig. 13, is toward the right. The work done in moving the wire in the plane to the left a distance of dx centimeters is given by $dw = \dfrac{Bi\,ds\,dx}{10}$ ergs.

Since a magnetic field is permeated by continuous tubes of flux the change of flux $(d\phi)$ surrounding or linking the displaced wire is $B\,ds\,dx$ maxwells. The work done on the wire during its displacement is then given by $dw = \dfrac{i\,d\phi}{10}$ ergs and represents the energy converted when the flux linking a current is changed by $d\phi$ maxwells. The energy converted by changing the flux linking N turns of wire is therefore given by

43 $$dw = \frac{Ni\,d\phi}{10}\text{ ergs.}$$

During an increase of flux the electric circuit loses energy and during a decrease of flux the electric circuit gains energy. If the current (i) in 43 is maintained at a constant strength of I amperes

while the flux linking the N turns is changed by a finite amount $\Delta\Phi$ maxwells, the energy converted by the change in flux, from 43, is given by

44 $$w = \frac{NI\,\Delta\Phi}{10} \text{ ergs.}$$

If the current (i) in 43 varies in strength while the flux linking the N turns is changed, the energy converted during a simultaneous change of current and flux is given by $w = \frac{N}{10}\int i\,d\phi$. When the flux linking an electric circuit is established by the current flowing in the circuit, the flux may be expressed by some function of the current and the energy converted during any change in the current may be determined by integration.

The flux linking any circuit located in a medium of constant permeability, from 37, is directly proportional to the current, or $\phi = Ki$. Since $d\phi = K\,di$, $w = \frac{NK}{10}\int i\,di$ and $w = \frac{NKi^2}{20}$, the limits being the initial and the final values of the current. The energy converted when the current in N turns of wire is increased from zero to I amperes is then given by $w = \frac{NKI^2}{20}$ ergs and, since $\Phi = KI$, the energy converted is also given by

45 $$w = \frac{N\Phi I}{20} \text{ ergs.}$$

The establishment of a current in any circuit is thus accompanied by a conversion of electric into magnetic energy, the amount of energy converted in any case being given by an integration of 43, and when the permeability of the surrounding medium is constant, by 45. When the current in any circuit is interrupted the magnetic energy stored in the surrounding medium is again converted into electric energy, either in whole or in part, depending upon the nature of the surrounding medium.

Space Distribution of Magnetic Energy. The magnetic energy (W) stored within the internal core of a toroidal coil (Fig. 20) of N turns conducting a current of I amperes (the permeability of the core being assumed constant), from 45, is $\frac{N\Phi I}{20}$ ergs. The volume (V) of a toroidal core of r centimeters mean radius and A square centimeters cross-sectional area when the area is small compared with the radius of the core is $2\,\pi rA$ cubic centimeters. The magnetic energy per cubic centimeter (w) stored in the toroidal core is therefore given by $w = \frac{N\Phi I}{20 \cdot 2\,\pi rA} = \frac{NBI}{40\,\pi r}$ ergs per cubic centimeter. The flux density in such a core, from 42, is given by $B = \frac{0.2\,NI\mu}{r}$ gausses. Substituting for I its equivalent, $\frac{5\,Br}{N\mu}$, $w = \frac{NB}{40\,\pi r}\cdot\frac{5\,Br}{N\mu}$ and the magnetic energy per cubic centimeter stored in any medium of constant permeability is given by

46 $$w = \frac{B^2}{8\,\pi\mu} \text{ ergs per cubic centimeter.}$$

Magnetomotive Force and Reluctance. Since the unit of flux, the maxwell, may be represented in space by a continuous tube of variable cross section the magnetic flux or the aggregate of the constituent tubes of flux may also be represented in space by a continuous volume of variable cross section. The magnetic energy (W_1) stored in any longitudinal section of this volume, l_1 centimeters in length, A_1 square centimeters in cross-sectional area, and filled with a medium of constant permeability (μ_1) (multiplying w in 46 by the volume of the section) is given by $W_1 = \frac{B_1^2 l_1 A_1}{8\,\pi\mu_1}$ ergs. The total magnetic energy stored in the magnetic field surrounding a circuit of N turns conducting a current of I amperes (the permeability of the surrounding medium being constant), from 45, is given by $W = \frac{N\Phi I}{20}$ ergs and must equal the sum of the energies stored in the constituent parts of the magnetic field. Hence $\frac{N\Phi I}{20} = \frac{B_1^2 l_1 A_1}{8\,\pi\mu_1} + \frac{B_2^2 l_2 A_2}{8\,\pi\mu_2} +$ etc. ergs. Though the flux density throughout a magnetic field may vary from point to point the flux through any cross section of the magnetic circuit is constant. Hence $\Phi = B_1A_1 = B_2A_2$, etc.,

and $\frac{N\Phi I}{20} = \frac{\Phi^2 l_1}{8\,\pi\mu_1 A_1} + \frac{\Phi^2 l_2}{8\,\pi\mu_2 A_2} +$ etc.

Then

$$1.26\,NI = \Phi\left(\frac{l_1}{\mu_1 A_1} + \frac{l_2}{\mu_2 A_2} + \text{etc.}\right)$$

or

47 $$\Phi = \frac{1.26\,NI}{\dfrac{l_1}{\mu_1 A_1} + \dfrac{l_2}{\mu_2 A_2} + \text{etc.}} \text{ maxwells.}$$

The resultant magnetomotive force (mmf) ($\mathcal{F}$) in a stated direction of several independent coils of wire wound upon the same magnetic circuit and conducting different currents is given by

48 $$\mathcal{F} = 1.26\,(\pm N_1 I_1 \pm N_2 I_2 \pm \text{etc.}) \text{ gilberts,}$$

where a positive or negative sign indicates that the associated mmf is acting respectively in the same or in the opposite direction to the stated direction.

The resultant reluctance ($\mathcal{R}$) of several longitudinal sections of a magnetic circuit of various respective lengths, cross-sectional areas, and permeabilities is given by

49 $$\mathcal{R} = \frac{l_1}{\mu_1 A_1} + \frac{l_2}{\mu_2 A_2} + \text{etc. gilberts per maxwell.}$$

The mmf required to establish a stated flux in a magnetic circuit of constant cross-sectional area (A square centimeters), length (l centimeters) and uniform permeability (μ), from 47, is given by $1.26\ NI = \Phi \dfrac{l}{\mu A}$. The number of ampere turns required per centimeter length of the magnetic circuit is therefore given by

50 $$nI = 0.796\,\frac{B}{\mu} \text{ ampere turns per centimeter length of the magnetic circuit.}$$

The Magnetization Curve. Since the permeability of all magnetic materials varies with the flux density equation 50, when applied to such materials, contains three variables, nI, B, and μ. If the corresponding values of B and nI are plotted for any material from test data nI may be determined easily without consideration of the value of μ. The curve obtained from such plotted values of B and nI for any material is called the magnetization curve

(Fig. 22) of the material. Magnetization curves of various materials are given on page 223. It will be noted that when nI is small, B increases sensibly in proportion to nI, but for higher values of nI, B increases less rapidly due to the decreasing permeability of the material. For all points above S on the curve the material is said to be saturated and for all points below S, unsaturated. The permeability of any material for any value of nI may be determined from its magnetization curve by substituting the corresponding value of B in 50 and solving for μ.

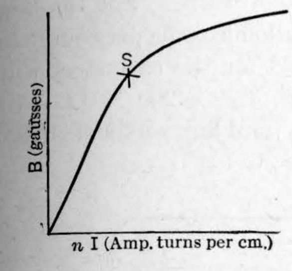


FIG. 22

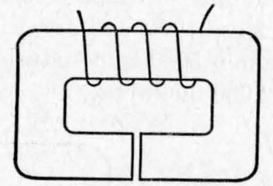


FIG. 23

In magnetic computations, Formulas 47, 49, and 50 may be applied only when the permeability is unity or has definite known values. Computations for magnetic circuits containing paramagnetic cores must be made in general by the methods explained in the following paragraph.

Typical Magnetic Computation. The magnetic circuit shown in Fig. 23 consists of cast steel, 20 inches in mean length and 4 square inches in cross-sectional area, and an air gap, 0.1 inch in length and with an assumed cross-sectional area the same as that of the steel. Suppose that we wish to determine the number of ampere turns that must be wound on the core to produce a total flux of 360,000 maxwells in the core. The flux density is $\dfrac{360{,}000}{4 \times 1000} = 90$ kilomaxwells per square inch. From the magnetization curve for cast steel on page 223 the number of ampere turns per inch required for the above flux density is 50. The total ampere turns for the cast steel alone will then be $50 \times 20 = 1000$ ampere turns. For the same flux density (page 223) the number of ampere turns per inch for the air gap is $142 \times 200 = 28{,}400$ ampere turns and for

0.1 inch it will be 0.1 × 28,400 = 2840 ampere turns. The total number of ampere turns required to produce a flux of 360,000 maxwells will then be 1000 + 2840 = 3840 ampere turns.

In the converse problem suppose the number of ampere turns wound on the same magnetic circuit is 5000. The total flux is obtained only by "cut and try." Let us assume that the flux density will be 100 kilomaxwells per square inch. Then from page 223, the cast steel will require 105 × 20 = 2100 ampere turns and the air gap will require 158 × 200 × 0.1 = 3160 ampere turns. The sum is 5260 ampere turns. For the second trial assume the flux density to be 98 kilomaxwells per square inch. The number of ampere turns required for the cast steel will be 95 × 20 = 1900 and for the air gap, 155 × 200 × 0.1 = 3100. The sum is 5000 ampere turns and the total flux will be 98,000 × 4 = 392,000 maxwells.

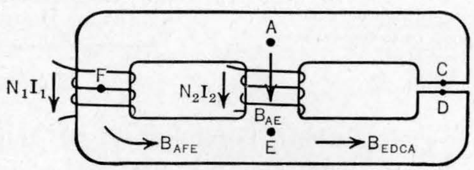


Fig. 24

When the magnetic circuits contain several branches as shown in Fig. 24 and the flux densities (B_{AFE}, B_{AE}, and B_{EDCA}) are given, the magnetic potential from A to E is the same by any path. Assuming the material to be wrought iron all determinations of the required ampere turns per inch will be obtained from the wrought iron curve on page 223. Then $+N_1I_1 - nI$ per inch (corresponding to B_{AFE}) × length (AFE) = $+N_2I_2 - nI$ per inch (corresponding to B_{AE}) × length (AE) = $+nI$ per inch (corresponding to B_{EDCA}) × length ($AC + DE$) + nI per inch (corresponding to B_{EDCA} in air) × length (CD). If, conversely, the number of ampere turns (N_1I_1 and N_2I_2) are given the flux density in each branch must be assumed and corresponding values of nI per inch must be substituted in the above equations until N_1I_1 and N_2I_2 agree with the stated values. The assumed values of the flux densities must conform to the general principle that the total flux (not flux density) flowing into a junction must equal that flowing away.

The Hysteresis Cycle. If the mmf per centimeter applied to any magnetic material is increased until the flux density reaches any value (such as $+B_m$ in Fig. 25) and is then reduced to zero, the values of B corresponding to the decreasing values of nI will be represented typically by the curve connecting $+B_m$ with B_p. At the point B_p the material retains a part of its former flux density in the absence of any external mmf and is called a permanent magnet. The property of any material by which it retains a part of its former magnetic flux after the mmf force is removed is called its retentivity. The greatest retentivity in magnetic materials having air gaps is found in hard steels and the least in soft iron. The most powerful permanent magnets consist of a granular alloy of iron, cobalt, nickel, and aluminum.

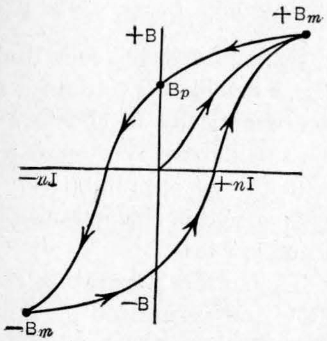


Fig. 25

The magnetic energy converted from electric energy during the application of an increasing mmf to a non-magnetic material (such materials possess no retentivity) is again converted into electric energy when the mmf is removed. In a magnetic material part of the magnetic energy is reconverted into electric energy and the rest remains stored in the magnetic circuit containing the magnetic material. If the mmf is now increased in the opposite direction the associated changes in flux density will be represented typically by the curve (Fig. 25) connecting B_p with $-B_m$. A reduction of mmf to zero, reversal, and increase in the initial

direction again will bring the flux density back to $+B_m$ along the lower curve (Fig. 25) connecting $-B_m$ with $+B_m$. The complete sequence of changes in B corresponding to nI represented in Fig. 25 is called the hysteresis cycle of the magnetic material and its graphical representation is called a hysteresis loop.

During the hysteresis cycle the magnetic energy not reconverted into electric energy is converted into heat. The energy lost in this manner in a magnetic material subjected to a reversing mmf (by applying the principle stated in 43 to a cubic centimeter of the material) is given by $w = \text{line} \int \frac{nI\, dB}{10}$ ergs per cubic centimeter, or the area enclosed by the hysteresis loop divided by 10. Since most types of electrical machinery contain a reversing magnetic flux it is important economically to choose a material having a hysteresis loop with a small area. Very pure iron has a hysteresis loop of small area but its cost is prohibitive. A fairly pure iron containing from 3 to 4 per cent of silicon is usually adopted because it has both low cost and low loss.

Magnetic Poles. The surface separating any two materials of different permeabilities and permeated by a magnetic flux is the apparent seat of a force acting upon magnetic materials and such a surface is called a magnetic pole. The surface through which the flux leaves a magnetic material of higher permeability is called a North pole and the surface through which the flux enters a magnetic material of higher permeability is called a South pole.

Force Between Two Magnetic Poles. When two magnetic materials are in contact or separated by an air gap and the flux density normal to the adjacent surfaces of the magnetic materials is B gausses the flux density will not be changed by a finite amount if the distance between the adjacent surfaces is increased by dx centimeters. If the area of each of the adjacent surfaces of the magnetic materials (Fig. 26) is A square centimeters the volume of the air gap will be increased by $A\, dx$ cubic centimeters. Since the additional energy stored in each cubic centimeter of the increased air gap, from 46, is $\frac{B^2}{8\pi}$ ergs (the permeability is 1 whether the surfaces are touching or not), the energy of the magnetic circuit as a whole is increased by $\frac{B^2 A\, dx}{8\pi}$ ergs. If F is the force required to increase the length of the air gap by dx centimeters the work done in moving one of the poles that distance will be $F\, dx$ ergs. Hence $F\, dx = \frac{B^2 A\, dx}{8\pi}$ and the force between the two poles is given by

51 $$F = \frac{B^2 A}{8\pi} \text{ dynes.}$$

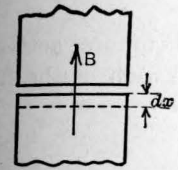


Fig. 26

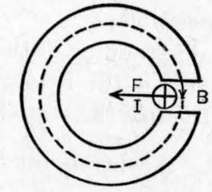


Fig. 27

In Fig. 27, the force acting on the wire, from 36, is given by $dF = \frac{BI\, ds \sin \alpha}{10}$ dynes. If B is produced by I, then I may be expressed as a function of B and the force acting on the wire is proportional to the square of the flux density. It will therefore be noted that the force between a wire conducting a current and a magnetic material, in which the flux is established by and is proportional to the same current, is also proportional to the square of the flux density established in the material.

General Principle of Force Action in a Magnetic Field. The force acting upon a current or a magnetic material placed in a magnetic field is in such a direction as to increase the flux linking the current or permeating the magnetic material. The source of the force action is actually the same in a magnetic material as with a current. In a magnetic material the spinning electrons constitute currents which react with the permeating magnetic flux. Such forces of magnetic origin also exist in non-magnetic materials but the vector sum of the individual forces in any direction is zero. The spinning electrons in a magnetic material under the influence of the permeating flux become oriented in position so that under increasing magnetization more and more of the individual forces act in the same direction. When saturated,

practically all the electrons involved spin in the same direction and further magnetization produces little effect. Most of the spinning electrons in soft iron with an air gap will turn back to their former neutral position when the permeating flux is removed. In hard steels most of the spinning electrons will remain oriented after the permeating flux is removed and we have a permanent magnet. Demagnetization may be produced only by applying an alternating flux of decreasing magnitude while the specimen is turned into all possible positions.

The understanding of the general principle of force action will be strengthened if the reader will apply it to each of the following cases and verify the stated results.

Case I. A wire conducting a current.

a. A bent wire will tend to straighten.
b. A circular wire will tend to increase its diameter.
c. A coil of two or more turns will tend to become more compact.

Case II. Two wires conducting currents.

a. Force of attraction between two currents flowing in the same direction.
b. Force of repulsion between two currents flowing in opposite direction.
c. Two currents making an angle with each other will tend to twist into the same plane with their currents flowing in the same direction.

Case III. A wire conducting a current, and a material.

a. A paramagnetic material will be attracted by the current to a position where the flux density due to the current is a maximum.
b. A diamagnetic material will be repelled.
c. A permanent magnet will tend to turn into a position such that the flux permeating it due to the wire and itself will be a maximum.

Case IV. A permanent magnet and a material.

a. A paramagnetic material will be attracted toward the nearer pole of the permanent magnet.

b. Several paramagnetic materials will be attracted as in (*a*) and also by each other, forming several chains.
c. Each pole of another permanent magnet will be attracted by the opposite pole and repelled by the like pole of the original permanent magnet.

Practice problems with answers for Chapter II will be found on pages 234 to 238.

CHAPTER III

ELECTROMAGNETIC INDUCTION

Emf Generated or Induced in a Material. It was demonstrated on page 25 that the work done in moving a wire ds centimeters in length conducting a current of I amperes through a magnetic field of B gausses flux density a distance of dx centimeters to the left, as shown in Fig. 28, is given by $dw = \frac{Bi\,ds\,dx}{10}$ ergs. The work done upon a wire of finite length (s centimeters) is then given by $dw = \frac{Bis\,dx}{10}$ ergs. The power, or rate at which work is done on the wire in moving it dx centimeters in dt seconds, is therefore given by $P = \frac{Bis\,dx}{10\,dt}$ ergs per second or $\frac{Bisv}{10^8}$ watts, where v is the velocity of the wire in centimeters per second.

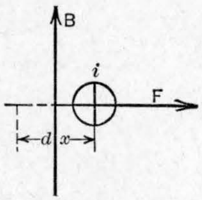


FIG. 28

The mechanical energy thus expended in moving the wire is converted into electric energy of the same amount which appears within the wire and its associated circuit. Hence the electric power developed by the motion of the wire in the magnetic field is also given by $P = \frac{Bisv}{10^8}$ watts and, since the process is reversible, the emf generated in the wire, from 1, is given by $e = \frac{Bisv}{i\,10^8}$ or $\frac{Bsv}{10^8}$ volts. If N conductors connected in series are moved simultaneously through a magnetic field under the conditions indicated in Fig. 28 and the emf generated in each conductor acts in the same direction in the series connection the total emf is given by

52 $$e = \frac{NBvs}{10^8} \text{ volts.}$$

Since each moving conductor (Fig. 28) is a source of electric power the direction of the emf (defined on page 3) is the same as that of the current. The relative directions of the motion (M), the flux density (B), and the emf (E) are shown in Fig. 29. If the directions of the motion and the flux density are indicated respectively by the thumb and forefinger of the right hand the direction of the emf is indicated by the middle finger.

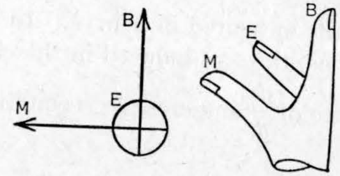


FIG. 29

Since a magnetic field is permeated by continuous tubes of flux the rate of change of the flux $\left(\frac{d\phi}{dt}\right)$ linking the N wires when moving at a velocity of v centimeters per second is Bvs maxwells per second and the emf generated in the N moving conductors or induced in the N conductors when the flux linking them changes at a rate of $\frac{d\phi}{dt}$ maxwells per second is given by

53 $$e = \frac{N}{10^8}\frac{d\phi}{dt} \text{ volts.}$$

The direction of a generated or induced emf may be determined by the right-hand rule or by the principle that the emf produced by a changing linkage flux acts in such a direction as to oppose (by the current it tends to establish) the change of linkage flux. The direction of the emf is therefore given by the direction of the current (Fig. 16) which will establish a flux in such a direction as to maintain the original magnitude and direction of the linkage flux.

Emf Induced in a Wire by a Change of Current in the Same Wire. When the flux linking N turns of wire is directly proportional to the current flowing in the wire, $\phi = Ki$ and $\frac{d\phi}{dt} = K\frac{di}{dt}$. The emf induced in the N turns of wire when the current flowing in the wire changes at a rate $\left(\frac{di}{dt}\text{ amperes per second}\right)$, from 53, is given by $e = \frac{NK}{10^8}\frac{di}{dt}$ volts. Since N, K, and 10^8 are constants (N and K are

constants of the circuit), a single constant (L) may be substituted for $\frac{NK}{10^8}$ and this constant is called the self-inductance of the circuit, measured in henrys. In any circuit of L henrys self-inductance, the emf induced in the circuit when its current changes at a rate of $\frac{di}{dt}$ amperes per second is therefore given by

54 $$e = L\frac{di}{dt} \text{ volts.}$$

The direction of the self-induced emf, in accordance with the general principle stated under 53, will be such as to oppose the change in linkage flux or the change in current. It will be noted that the self-inductance of a circuit produces a steadying effect upon the current and is analogous to the mass property of matter which steadies the motion of matter through space.

The Self-inductance of a Wire. The self-inductance of any formation of wire may be determined from the ratio of the flux linking the wire to the current flowing in the wire which produces the linkage flux. This ratio (K) multiplied by the number of turns (N) linked by the flux and divided by 10^8 gives the self-inductance of the wire. The value of K may be determined by an integration of 37; the self-inductance of two parallel wires, for example, conducting the same current in opposite directions (the transmission line), determined by integrating the flux permeating the space between the wires and the wires themselves, is given by

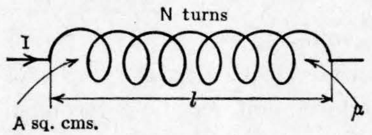


FIG. 30

55 $$L = \left[0.0805 + 0.741 \log \frac{D}{r}\right] 10^{-3} \text{ henrys per wire per mile.}$$

D is the distance between the centers of the wires and r is the radius of each wire, D and r being measured by any unit of length provided the same unit is used for both.

In simpler cases, K may be determined by substituting the constants of the circuit in 47. In a long solenoid of wire (Fig. 30), from 47, assuming the reluctance of the magnetic circuit outside

of the coil to be negligible

$$\Phi = \frac{1.26\,NI}{\frac{l}{\mu A}} = \left(\frac{1.26\,N\mu A}{l}\right) I$$

and

$$K = \frac{1.26\,N\mu A}{l}.$$

Hence

56 $$L = \frac{1.26\,N^2\mu A}{l \times 10^8} \text{ henrys.}$$

It will be noted that the self-inductance of any formation of wire depends upon its geometrical constants and the nature of the surrounding medium. The self-inductance is independent of the current if the wire is surrounded by a medium of constant permeability, but if the permeability of the medium is not constant, the self-inductance of the wire is a variable depending upon the magnitude of the current. The self-inductance of any formation of wire linked by Φ maxwells ($\Phi \propto I$) when conducting I amperes, substituting $\frac{\Phi}{I}$ for K in $L = \frac{NK}{10^8}$, is given by

57 $$L = \frac{N\Phi}{10^8\,I} \text{ henrys.}$$

Emf Induced in a Wire by a Change of Current in Another Wire. In Fig. 31 if the flux (ϕ_2) linking coil (2) due to a current (i_1) in

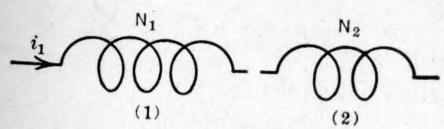


FIG. 31

coil (1) is directly proportional to i_1, or $\phi_2 = K'i_1$, then $\frac{d\Phi_2}{dt} = K'\frac{di_1}{dt}$ and from 53, $e_2 = \frac{N_2K'}{10^8}\frac{di_1}{dt}$. Since N_2, K', and 10^8 are constants (N_2 is a constant of coil (2) and K' is a constant involving the

geometrical constants of both coils and the nature of the surrounding medium) a single constant (M) may be substituted for $\frac{N_2K'}{10^8}$ and this constant is called the mutual-inductance of the two coils, measured in henrys. In two circuits of M henrys mutual-inductance the emf induced in one circuit when the current in the other circuit changes at a rate of $\frac{di_1}{dt}$ amperes per second is given by

58 $$e_2 = M\frac{di_1}{dt} \text{ volts.}$$

The Mutual-inductance of Two Wires. The mutual-inductance of two formations of wire may be determined from the ratio of the flux linking wire (2), due to a current (i_1) in wire (1), to the current in wire (1). This ratio (K') multiplied by the number of turns in wire (2), linked by the flux established by the current in wire (1), and divided by 10^8 gives the mutual-inductance of the two wires. The value of K' may be determined by an integration of 37 or, in simpler cases, by substituting the constants of wire (1) in 47 and determining the amount of flux due to the current in wire (1) that links wire (2). In the case of two long solenoids wound together on the same core (Fig. 32) the flux (Φ_1) due to the current (I_1) flowing in solenoid (1), from 47, is given by

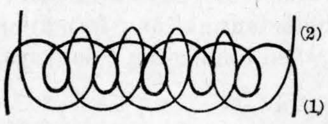


Fig. 32

$$\Phi_1 = \frac{1.26\,N_1I_1}{\frac{l_1}{\mu_1A_1}} \quad \text{or} \quad \left(\frac{1.26\,N_1\mu_1A_1}{l_1}\right)I_1.$$

Since the same flux links solenoid (2),

$$K' = \frac{1.26\,N_1\mu_1A_1}{l_1}$$

and

59 $$M = \frac{1.26\,N_1N_2\mu_1A_1}{l_1 \times 10^8}\text{ henrys.}$$

Self-inductance of a Series Connection. Given the self-inductances (L_1, L_2, L_3, etc.) of the respective parts of a series connection in which there is no mutual-inductance between the respective parts the resultant self-inductance of the series connection is given by

60 $$L = L_1 + L_2 + L_3 + \text{etc. henrys.}$$

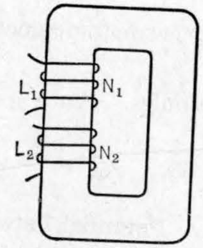


Fig. 33

If two coils are wound on the same core of constant permeability as shown in Fig. 33 and all the flux due to one passes through the other, the self-inductances may be represented, from 56, by $L_1 = kN_1^2$ and $L_2 = kN_2^2$, the constant (k) being the same for each coil. If these coils are connected in series, with their fluxes in conjunction, the resultant coil will have $(N_1 + N_2)$ turns and its self-inductance will be $L_3 = k(N_1 + N_2)^2 = kN_1^2 + 2\,kN_1N_2 + kN_2^2$. Since $N_1 = \sqrt{\frac{L_1}{k}}$ and $N_2 = \sqrt{\frac{L_2}{k}}$, $2\,kN_1N_2 = 2\sqrt{L_1L_2}$ and $L_3 = L_1 + 2\sqrt{L_1L_2} + L_2$. It will be noted, from 59, that $M = kN_1N_2 = \sqrt{L_1L_2}$.

If the coils are connected in series but with their fluxes opposing, the resultant coil will have $(N_1 - N_2)$ turns and $L_3 = L_1 - 2\sqrt{L_1L_2} + L_2$. The mutual-inductance of two coils is directly proportional to the percentage p (expressed as a decimal) of the flux due to one coil that links the other. The mutual-inductance (M) for any degree of coupling will then be $p\sqrt{L_1L_2}$. Taking into account all the conditions the self-inductance of two coils connected in series is given by

61 $$L = L_1 \pm 2\,p\sqrt{L_1L_2} + L_2 \text{ henrys}$$

and the mutual-inductance is given by

62 $$M = p\sqrt{L_1L_2}\text{ henrys.}$$

When three or more coils are connected in series the self-inductance may be computed in pairs by 61 until the resultant of all the coils is obtained.

The resultant self-inductance of a parallel connection depends upon the division of the current among the parts of the parallel connection and cannot be stated in terms of the respective self-

inductances of its constituent parts. This subject is discussed further on page 113.

Energy Required to Establish a Current. When the flux (Φ) linking the N turns of an electric circuit is directly proportional to the current (I) flowing in the circuit, the energy converted from electric to magnetic, from 45, is given by $W = \frac{N\Phi I}{20}$ ergs or $\frac{N\Phi I}{2 \times 10^8}$ joules. Since $\Phi = KI$, $W = \frac{NKI^2}{2 \times 10^8}$ and, substituting L for $\frac{NK}{10^8}$,

63 $$W = \tfrac{1}{2} LI^2 \text{ joules.}$$

Potential between Two Points in a Series Connection Conducting a Variable Current. When the current flowing between the two points a and b in Fig. 34 is constant the potential between

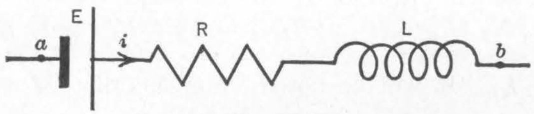


FIG. 34

a and b, from 6, is given by $V_{ab} = +E - IR$. If the current flowing from a to b is variable and the series connection between a and b possesses self-inductance, the potential between a and b, combining 6 and 54, is given by

64 $$v_{ab} = +E - iR - L\frac{di}{dt}$$

where E, i, and R are defined as in 6, L is the self-inductance between a and b, and $\frac{di}{dt}$ is the rate of change of the current; $\frac{di}{dt}$ is positive when the current flowing from a to b is increasing and is negative when the current flowing from a to b is decreasing.

Current Flowing at Any Instant in a Series Connection. In a series connection containing a constant emf (E), resistance (R), and self-inductance (L), as in Fig. 35, the potential between the two points a and b becomes zero when the switch is closed and, from 64, $+E - iR - L\frac{di}{dt} = 0$. This is a linear differential equation

of the first order and first degree, and its solution gives

65 $$i = \frac{E}{R}\left(1 - \epsilon^{-\frac{Rt}{L}}\right) + I\epsilon^{-\frac{Rt}{L}} \text{ amperes}$$

where i is the current flowing in the circuit t seconds after any change is made (such as closing the switch), ϵ is the base of the natural system of logarithms (2.718), and I is the current flowing in

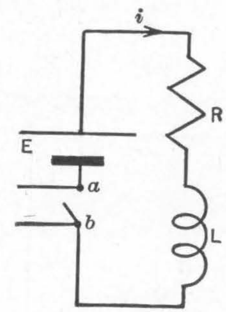


FIG. 35

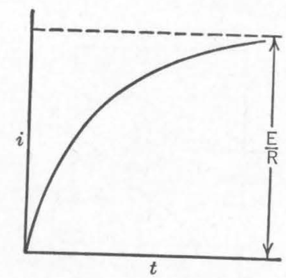


FIG. 36

the connection at time ($t = 0$) in the direction of the ultimate current. I is negative if the original current flows in the opposite direction to the ultimate current.

If the current flowing in the circuit when the switch is closed ($t = 0$) is zero, 65 reduces to

66 $$i = \frac{E}{R}\left(1 - \epsilon^{-\frac{Rt}{L}}\right) \text{ amperes.}$$

The curve represented by 66 is plotted in Fig. 36 and indicates that the current in such a circuit increases from zero to its ultimate value $\left(\frac{E}{R}\right)$ at a diminishing rate. The time required for the current to reach its approximate ultimate value (an infinite time is required to reach its actual ultimate value) is proportional to the ratio $\left(\frac{L}{R}\right)$, called the time constant of the circuit. When $\frac{L}{R}$ is small, the current increases rapidly and when $\frac{L}{R}$ is large the current increases slowly.

If the switch in Fig. 35 without an external connection is suddenly thrown to a', as in Fig. 37, the emf (E) in 65 is eliminated from the circuit and 65 reduces to

$$i = I\epsilon^{-\frac{Rt}{L}} \text{ amperes,} \tag{67}$$

where i is the current flowing in the circuit t seconds after the switch is thrown to a', R equals $R_1 + R_2$, and I is the current flowing in R_1 and L at time $(t = 0)$.

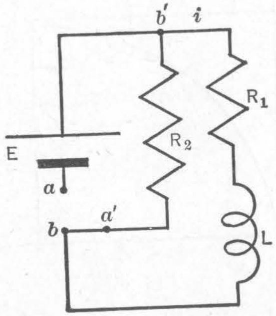


Fig. 37

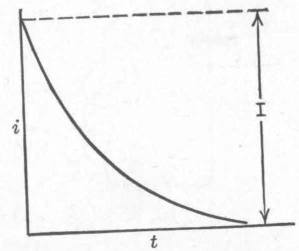


Fig. 38

The curve represented by 67 is plotted in Fig. 38 and indicates that the current diminishes from its initial value to zero at a diminishing rate. The time required for the current to reach zero approximately (an infinite time is required to reach zero exactly) is proportional to the ratio $\left(\frac{L}{R_1 + R_2}\right)$, called as before the time constant of the circuit. When $\frac{L}{R_1 + R_2}$ is small, the current decreases rapidly and when $\frac{L}{R_1 + R_2}$ is large the current decreases slowly.

Since the initial value of the current flowing through R_1, L, and R_2 is the same as that flowing through R_1 and L just before the emf (E) was eliminated from the circuit, the initial potential between a' and b' $(v_{a'b'} = -IR_2)$ may be many times greater than the original emf impressed upon the circuit.

Practice problems with answers for Chapter III will be found on pages 238 to 244.

CHAPTER IV

THE DIRECT-CURRENT DYNAMO

Application of the Dynamo. A dynamo is designed for the continuous conversion of mechanical into electric energy or the reverse. When mechanical energy is converted into electric energy the dynamo is called a generator and when electric energy is converted into mechanical energy the dynamo is called a motor. The power delivered from a dynamo is called its load. Generators are usually driven at constant speed at all loads while motors may vary in speed with the load, the character of the speed variation always depending upon the type of motor.

Construction of the Dynamo. The principal features of construction of direct-current dynamos intended for either generator or motor action are essentially the same. All direct-current dynamos contain a stationary structure called the frame and a rotating structure called the armature. The frame includes the base, the field core, and the members which support the armature bearings. The field core, which forms part of the magnetic circuit of the dynamo, may contain a single path as in Fig. 39 (a) or several paths as in 39 (b) and 39 (c). The parts of the field core adjacent to the armature are called the field poles and the remainder of the field core is called the field yoke. Dynamos may be

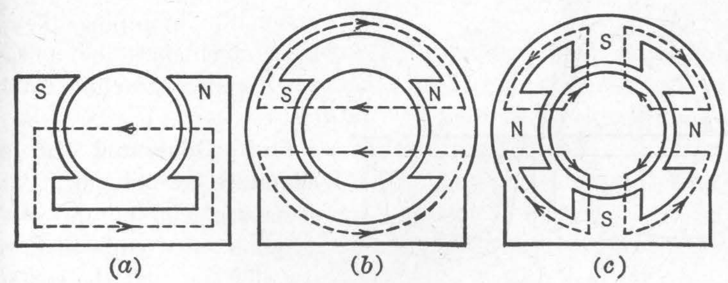
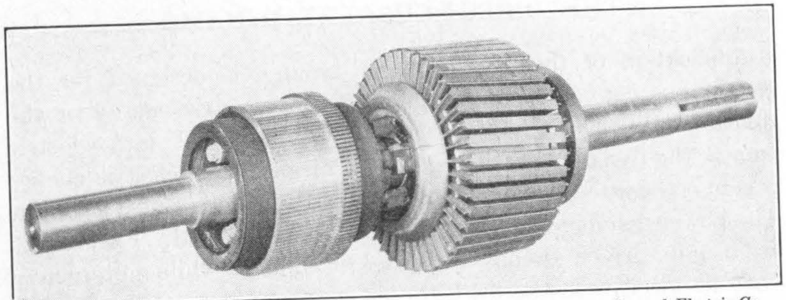


Fig. 39

constructed with field cores containing any multiple of two field poles; examples of bipolar construction are indicated in Figs. 39 (*a*) and 39 (*b*), and an example of multipolar construction (a four-pole field core) is indicated in Fig. 39 (*c*). The field core may consist of a single steel casting which includes the base of the dynamo



General Electric Co.

Unwound Direct-current Armature.

or may consist of several parts bolted together. The poles are usually constructed of laminated sheet iron and in most cases the entire field core is of laminated construction. The armature core is built up of laminated sheet iron stampings keyed to a steel shaft or a cast steel spider attached to the shaft.

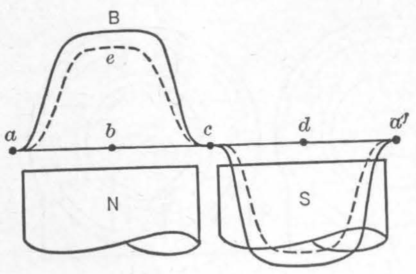
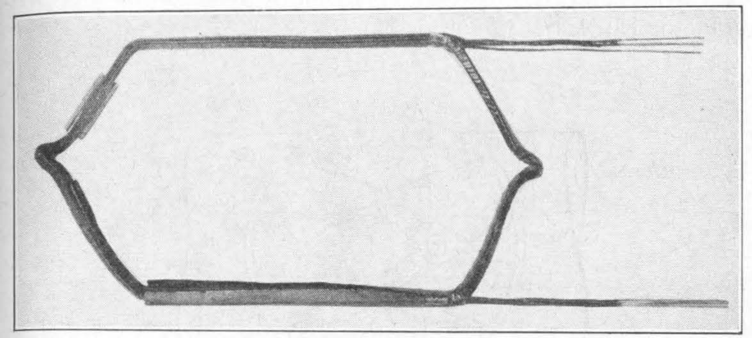


FIG. 40

Emf Generated in an Armature Conductor. The armature conductors of a dynamo are embedded in parallel slots on the surface of the armature core. The distribution of the flux density normal to the surface of the armature core under two poles may be represented typically by the curve (*B*) shown in Fig. 40. Since the emf generated in a moving conductor, from 52, is proportional to the flux density normal to its plane of motion, the emf generated at any instant in each armature conductor as it moves from *a* to *a'* must therefore vary in the same manner as the flux density. The emf (curve *e*) generated in each moving conductor is therefore zero at *a*, a positive maximum at *b*, zero at *c*, a negative maximum at *d*, zero at *a'*, etc. An emf which varies in this manner is called an alternating emf and is discussed in detail on page 97. It will be noted that the



General Electric Co.

Partly Completed Armature Coil for a Direct-current Generator or Motor.

wave form of the emf depends only upon the distribution of the flux density in the air gap. The flat-topped wave shown in Fig. 40 is most desirable in a direct-current dynamo but a sinusoidal wave, as explained later, is the best form for an alternating-current dynamo.

The Bipolar Drum Winding. To impress a direct emf upon a circuit connected to such a dynamo the armature conductors must be connected to each other and to the external circuit so that the emf's of all conductors in the armature which are connected in series will act in the same direction throughout that connection at any instant and the positive terminal of each of these series connections must be connected continuously to the positive terminal of the external circuit.

The manner in which these requirements are satisfied in the bipolar dynamo is illustrated in Fig. 41. The various conductors on the armature are connected front and back to form an endless winding, called a drum winding. Each front connection is attached to a segment in a multi-segment ring, called a commutator, and the connections to the external circuit are made through two brushes which rest upon the commutator at diametrically opposite points. The direction of the emf and, in consequence, the

direction of the current in each conductor is determined by the right-hand rule and is indicated in the figure. It will be seen that the negative brush, for example, must be located in the position shown so that the current flowing into the armature at that brush may divide and flow through two paths, one beginning with conductor No. 1 and the other No. 6.

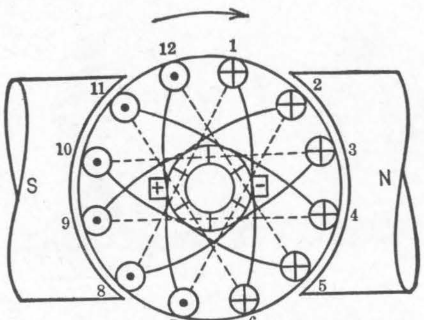


FIG. 41

For the position of the armature shown in Fig. 41, the armature conductors are connected to the external circuit as shown diagrammatically in Fig. 42. The emf generated in each conductor at this instant is shown in magnitude and direction in Fig. 43. Since the

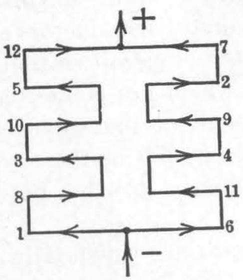


FIG. 42

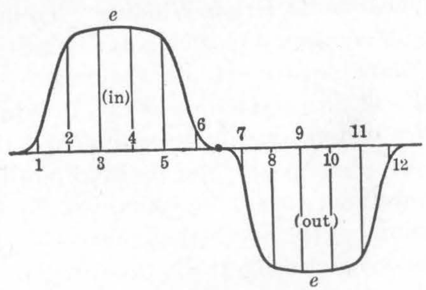
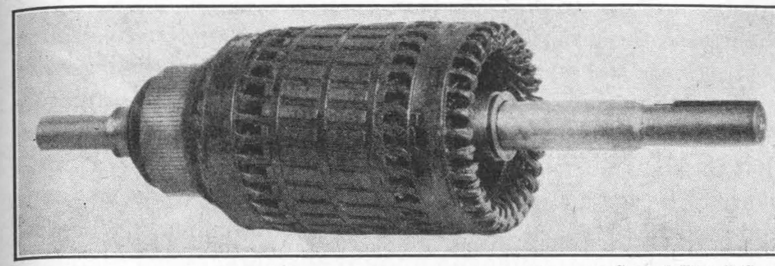


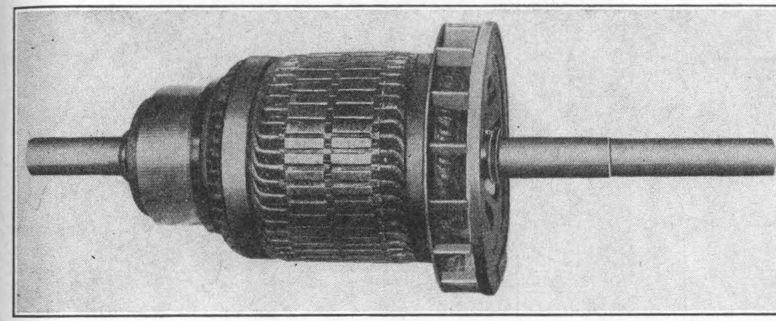
FIG. 43

emf generated in each conductor varies during one revolution as shown in Fig. 43 the individual emf's generated in the various conductors at any instant are not necessarily the same. The aggregates of the emf's generated in each path for any position of the armature are the same by reason of the symmetry of the wind-



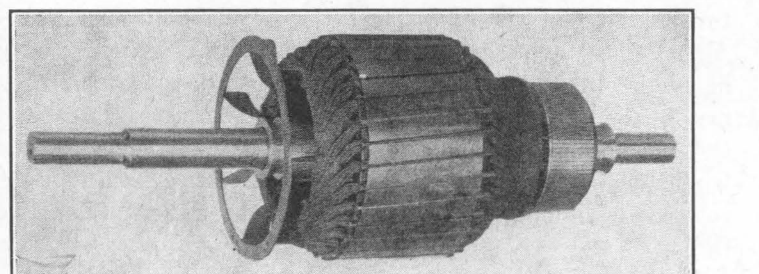
General Electric Co.

Direct-current Motor Armature.



Westinghouse Electric and Manufacturing Co.

Direct-current Motor Armature with Ventilating Fan.



General Electric Co.

Direct-current Motor Armature with Skewed Slots and Ventilating Fan.

ing, but are not constant. The emf generated between the brushes will be unidirectional in such a dynamo but will vary slightly as the armature rotates, the magnitude of the variation being less as the number of commutator segments is increased.

The Multipolar Drum Winding. The size of the armature conductors in any dynamo depends upon the maximum current that the dynamo is expected to carry continuously. The number of armature conductors is determined by the speed of the armature and the emf to be generated in the armature winding. When the space requirement of the armature conductors becomes large by

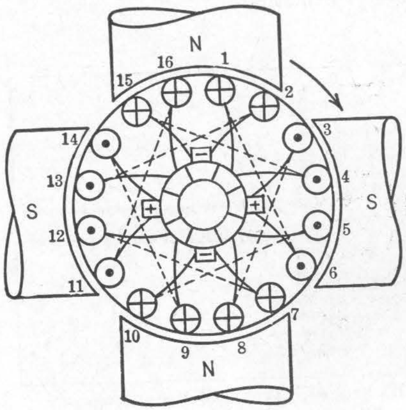


Fig. 44

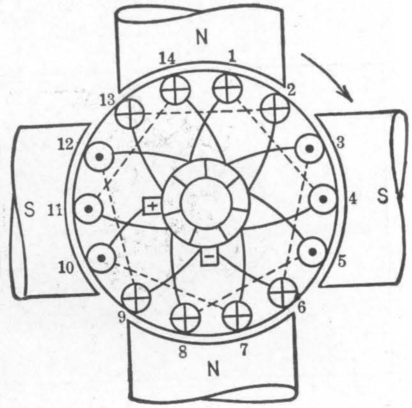
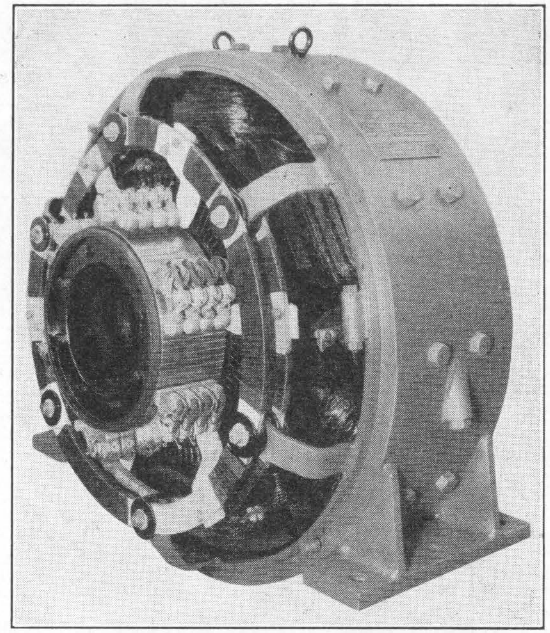


Fig. 45

reason of their size or number the requisite diameter of the armature may for many reasons suggest the use of a multipolar field core. Among the advantages of multipolar windings are (1) a shorter magnetic circuit, (2) less current per brush because more brushes may be used, (3) easier placement in manufacture of coils spanning shorter chords, and (4) better appearance. Two types of drum winding may be employed in connection with a multipolar field core, a lap winding (shown in Fig. 44) and a wave winding (shown in Fig. 45).

In the lap winding the conductors are joined by alternate forward and backward connections whereas in the wave winding the conductors are joined by successive forward connections. In the lap winding the number of paths (m) and the number of brushes

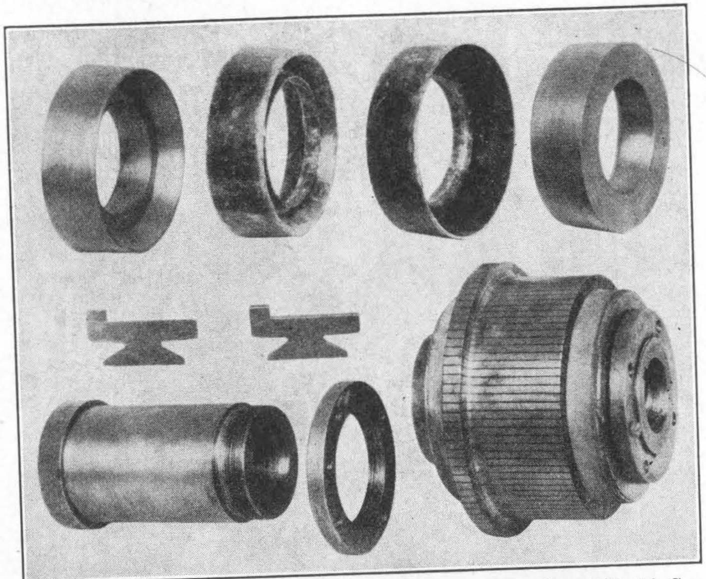
(b) equals the number of poles (p). In the wave winding $m = 2$, and $b = 2$ or any even number of brushes up to p. Although two brushes may be employed theoretically in connection with the multipolar wave winding a shorter commutator is obtained by the use of p brushes.



General Electric Co.

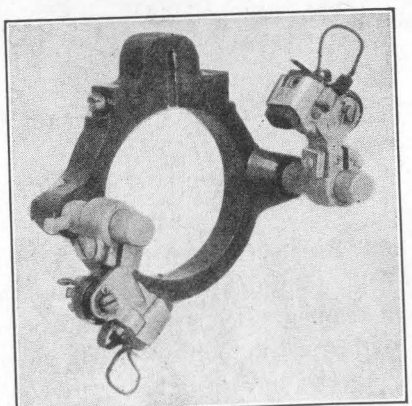
Six-pole Direct-current Compound Generator without Shaft and Bearings.

Commutator and Brush Construction. A commutator consists of a ring of copper segments clamped between two cast-iron spiders, the copper segments being insulated from each other and from the spiders by reconstructed mica. The number of commutator segments equals the number of armature conductors divided by an integer. Although it is desirable to employ as large a number of commutator segments as possible to reduce the pulsations of the generated emf between brushes a large number of commutator segments implies a large diameter of the commutator and the



General Electric Co.

Commutator Construction for a Direct-current Motor.

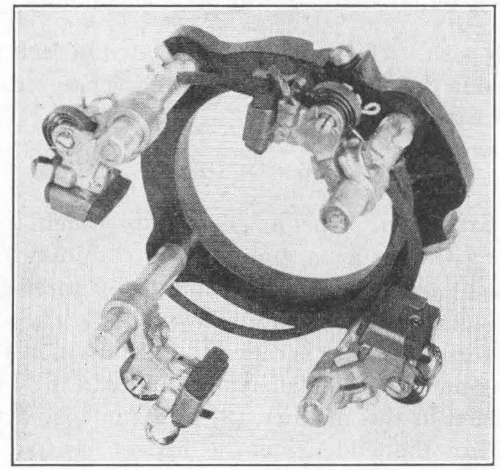


General Electric Co.

Brush Rigging for a Two-pole Direct-current Motor.

number of segments may be limited by the speed of the brush over the surface of the commutator at which satisfactory commutation may be obtained.

Brushes, usually made of carbon, are supported by brush holders which maintain sufficient pressure of the brushes on the commutator to obtain proper contact without excessive wear. The



General Electric Co.

Brush Rigging for a Four-pole Direct-current Motor.

brush holders are attached to a brush yoke by insulated studs. The brush yoke is bolted to the frame of the dynamo and in some cases is adjustable as to position so that the brushes may be moved together through an angle around the commutator to improve commutation.

Emf Generated in a Drum-wound Armature. If S equals the rotational speed of an armature in revolutions per minute the time required for one revolution is $\frac{60}{S}$ seconds and the time required for one conductor to pass through the space between two consecutive interpolar planes is $\frac{60}{pS}$ seconds. If Φ is the total flux entering or leaving each pole the average rate at which each conductor cuts

magnetic flux is $\frac{\Phi}{\frac{60}{pS}}$ or $\frac{\Phi pS}{60}$ maxwells per second. The average emf generated in each conductor, from 53, is then given by $E_{av} = \frac{\Phi pS}{6 \times 10^9}$ volts. If there are Z conductors on the armature and m paths between terminals there will be $\frac{Z}{m}$ conductors connected in series in each path. Hence the emf generated in each path, or the emf generated in the armature, is given by

68 $$E_a = \frac{Z\Phi pS}{6\, m \times 10^9} \text{ volts.}$$

Dynamo Excitation. The magnetic flux which traverses the armature core, the air gaps, and the field core may be produced by a permanently magnetized field core or by passing an electric current through coils wound on the field poles. The source of the magnetic flux in either case is called the excitation of the dynamo. Excitation by permanent magnetism is limited (1) by the low flux density attained in this manner, (2) by its inflexibility of adjustment, and (3) by the tendency of the flux density to decrease with age, vibration, and temperature changes. Permanent excitation is used extensively, however, in small dynamos (called magnetos) in connection with gas engine ignition systems, in certain types of speed indicators, and in small motors.

Armature Reaction. In any dynamo operated at no load the distribution of the flux density in the air gaps due to the ampere turns wound on the field poles will be symmetrical about the interpolar plane as shown in Fig. 46. The nature of the distribution will depend upon the span and shape of the pole faces.

When the same dynamo is operated under load the ampere turns on the armature will produce a flux (Φ_a) perpendicular to the flux (Φ_f) due to the main field. The mmf due to the ampere turns on the armature, called the armature reaction, produces two undesirable effects. It will distort the distribution of the flux density in the air gaps as shown in Fig. 47 and in consequence distort the wave form of the emf generated in each conductor on the armature. The increased flux density at the trailing pole tips

will saturate the poles in those regions and reduce the total flux entering and leaving the armature, and cause a similar reduction of the generated emf. The reducing effect is usually measured by demagnetizing ampere turns. In a later discussion of the

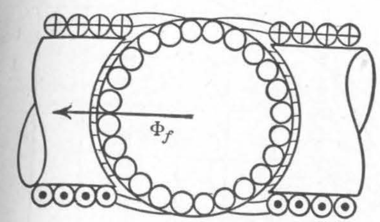


FIG. 46

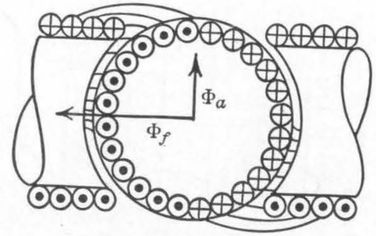


FIG. 47

theory of commutation it will be shown that auxiliary or commutating poles may be added to a dynamo, which will compensate for changes in flux in certain parts of the armature winding and will automatically establish sparkless commutation at all loads.

Self-excitation. The current established in the field winding of a dynamo may be due to an external emf (separate excitation) or to the emf generated in the armature (self-excitation). In either case (neglecting the effect of armature reaction) the field flux (Φ_f) corresponding to any value of field current (I_f) will be represented by a curve as shown in Fig. 48. Since the generated emf at any stated speed is directly proportional to the flux per pole, a plot of the generated emf (E_a) and the field current (I_f) with the armature speed held constant will be of the same form as that shown in Fig. 48.

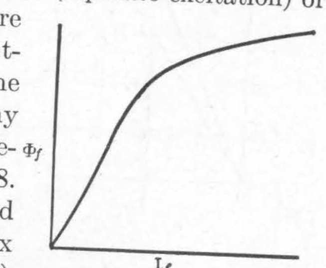


FIG. 48

Corresponding values of generated emf and field current are plotted in Fig. 49 for a dynamo operated at constant speed. If the excitation of a dynamo is provided by an external source of emf (E_b) and the emf generated in the armature of the dynamo is of the same magnitude (E_a), it is evident (neglecting the resistances of the external source and the resistance of the armature) that the armature will continue to generate the same emf if the field switch (Fig. 50) is thrown to the right.

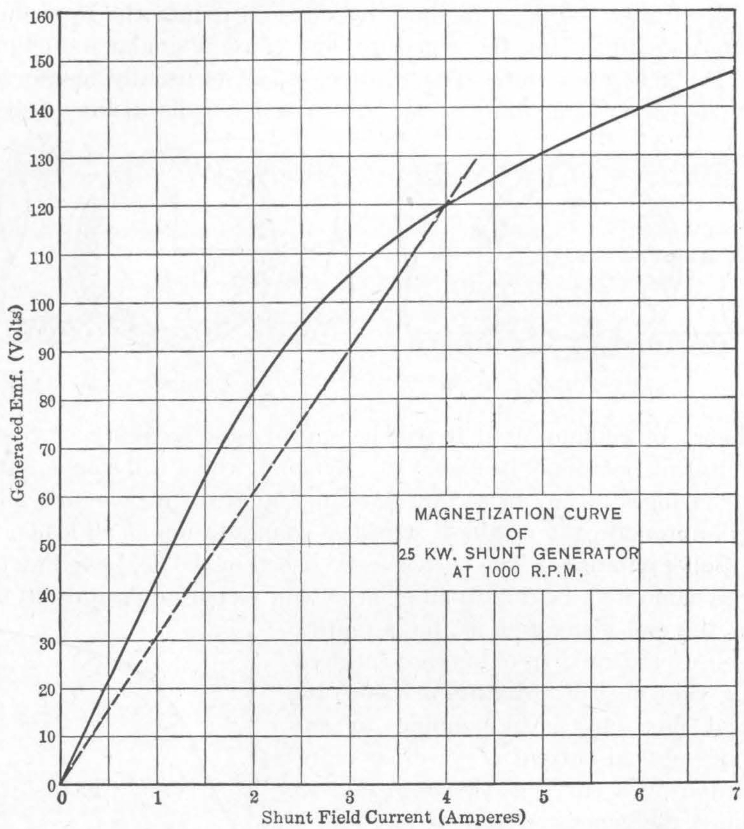


FIG. 49

The Shunt Generator. A dynamo operating as a generator and self-excited by a field winding connected to the armature terminals as shown in Fig. 51 is called a shunt generator. It is usually unnecessary to employ an external source of excitation to obtain the initial generation of emf in the armature of the shunt generator since the magnetic circuit will in general be traversed by a small amount of flux due to the permanent magnetism of the field core. A small emf will therefore be generated in the armature in consequence of its rotation and this emf will establish a small current in the field winding. If the mmf due to this field current

assists the initial permanent mmf the resultant flux will be increased. The generated emf, field current, and field flux will then increase simultaneously as shown in Fig. 52 and the generator is said to "build up."

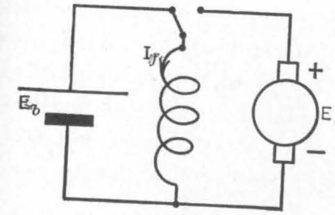


FIG. 50

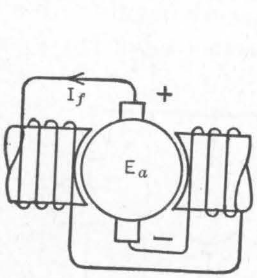


FIG. 51

In the circuit shown in Fig. 51, $E_a = i_fR_c + L_c \dfrac{di_f}{dt}$, where R_c equals the sum of the field and armature resistances and L_c equals the sum of the field and armature inductances; both inductances vary widely during the "building-up" period. It is evident that E_a will stop increasing only when i_f stops increasing or when $\dfrac{di_f}{dt}$ equals zero. This point on the magnetization curve may be determined graphically, as follows: Suppose the shunt field resistance (including the rheostat) is 30 ohms and the armature resistance in comparison is negligible. Multiply any shunt field current, such as 3 amperes in Fig. 49, by 30 ohms and find the emf (90 volts) required to establish that steady current. We will then draw a straight line from the origin through the (3 ampere-90 volt) point. The intersection of this resistance line with the magnetization curve gives the emf (120 volts) to which the emf will "build up" at an armature speed of 1000 rpm. It will be noted that when the shunt field current is 3 amperes, for example, the generated emf is 106 volts. Since i_fR_c is 90 volts (neglecting i_fR_a) then $L_c \dfrac{di_f}{dt}$ must be 16 volts and $\dfrac{di_f}{dt}$ has a finite value. When the generated emf reaches 120 volts, i_fR_c equals 4×30 or 120 volts

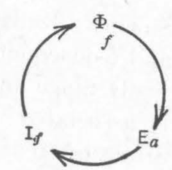


FIG. 52

and $L_c \frac{di_f}{dt}$ and, in consequence, $\frac{di_f}{dt}$ equals zero. If the resistance line and the magnetization curve do not intersect, the generator will not "build up." If a line is drawn from the origin tangent to the magnetization curve the ratio of any ordinate to this line to the corresponding abscissa is called the critical resistance of the shunt field. When operating under that condition a slight decrease in speed or increase in shunt field resistance will cause the generated emf to drop to zero or to a small value due to residual magnetism.

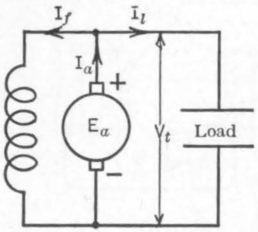


FIG. 53

The armature current of a shunt generator operated at no load equals the field current, but when a load is connected to the generator terminals the armature current equals the sum of the field current and the line current as shown in Fig. 53. The application of load to the shunt generator is accompanied by a decrease in terminal potential for the following reasons:

(1) The terminal potential of a shunt generator, from 6, is given by $V_t = E_a - I_aR_a$. If E_a is first assumed to remain constant it is evident that V_t must decrease as I_a increases.

(2) The field current of a shunt generator is given by $I_f = \frac{V_t}{R_f}$. Since V_t decreases with an increase of load as indicated in (1) I_f, and (consequently) Φ and E_a must decrease.

(3) Since an increase in armature current is associated with an increase in load the armature reaction by distortion will cause the air gap flux and the generated emf (E_a) to decrease.

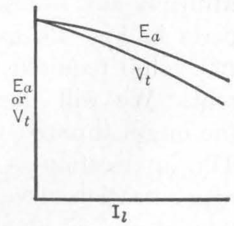
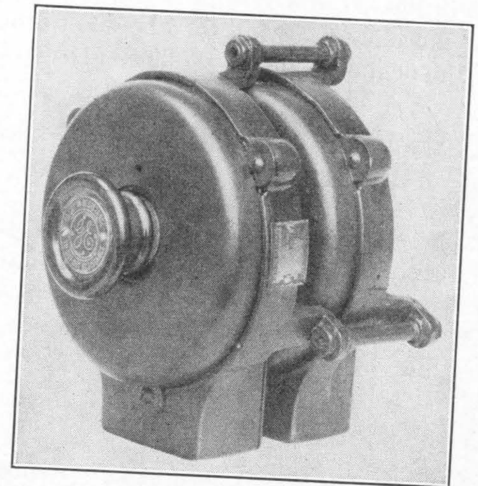


FIG. 54

A plot of corresponding values of E_a and I_l (called the internal characteristic) and corresponding values of V_t and I_l (called the external characteristic) for a shunt generator under increasing load are shown in Fig. 54. In a properly designed generator with low armature resistance and low demagnetizing mmf the change of terminal potential from no load to full load is usually less than 5 per cent. The terminal potential

may be held constant for any load or made higher than at no load by manual or automatic adjustment of the shunt field resistance.


General Electric Co.

Enclosed Shunt Generator or Motor Field Rheostat.

Automatic regulation of the terminal potential of shunt generators may be effected in many ways. A simple form, known as a "Tirrill" regulator, is illustrated in Fig. 55. If V_t is too low the current (I_c) in the electromagnet is insufficient to hold up the plunger which drops and short-circuits a resistance (R) in series with the shunt field winding. This is followed by an increase in I_f, Φ_a, E_a, and V_t. If V_t is now too high, I_c increases and lifts the plunger, removes the short-circuit on R, and I_f, Φ_a, E_a, and V_t decrease. The plunger or a magnetic reed thus vibrates back and forth and maintains V_t substantially constant. The actual regulator contains many more parts than those shown but the principle is the same as indicated in the simpler construction.

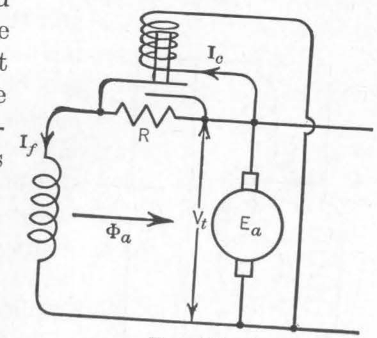


FIG. 55

The Series Generator. When the excitation of a dynamo operated as a generator is furnished by the line current flowing through field coils connected in series with the load and the armature, as shown in Fig. 56, the dynamo is called a series generator. The generated emf at no load will then be due to the permanent magnetism of the field core and as the line current (I_l) increases,

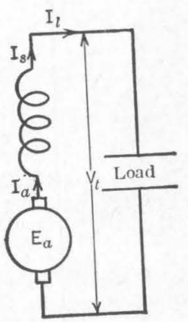


FIG. 56

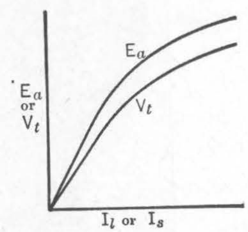


FIG. 57

since $I_l = I_s = I_a$, the generated emf (E_a) will increase as shown in Fig. 57. The terminal potential (V_t) for any value of the load will be less than E_a by an amount equal to $I_aR_a + I_sR_s$ as shown in Fig. 57. The upper curve in Fig. 57 is the internal characteristic and the lower curve the external characteristic of the series generator. Such a generator is obviously not adapted to a constant potential system operating under variable load. Although employed to some extent in connection with series street lighting systems operated at constant current and variable potential the series generator at present has very few applications.

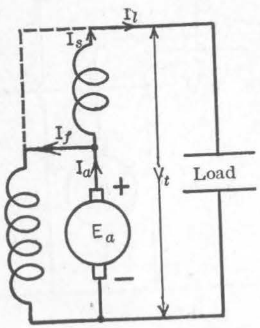
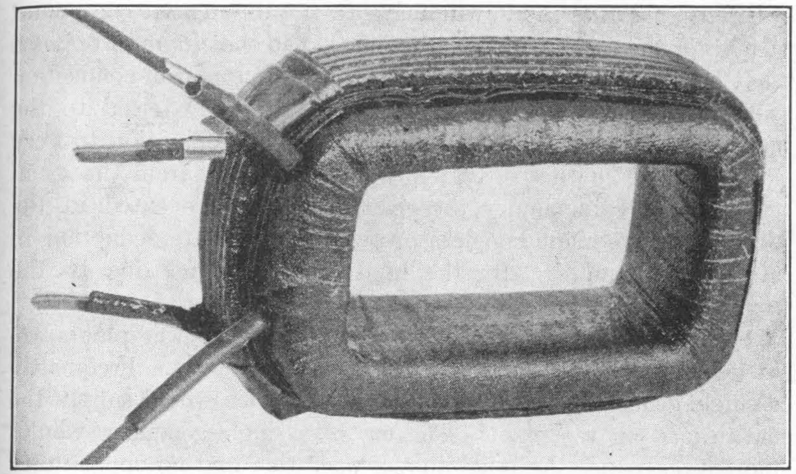


FIG. 58

The Compound Generator. A generator equipped with both shunt and series field windings and called a compound generator (Fig. 58) may be employed with advantage in many instances. The generator is called a short-shunt compound generator when

the shunt winding is connected across the brushes and is called a long-shunt compound generator when the shunt winding is connected across the line terminals. Since the terminal potential of a shunt generator decreases with an increase of load and the terminal potential of a series generator increases with an increase



General Electric Co.

Shunt and Series Field Winding for a Direct-current Motor.

of load, by combining the two windings in various proportions the terminal potential may be made to increase (over-compounded), remain sensibly constant (flat-compounded) or decrease (under-compounded) as the load increases as shown in Fig. 59. The degree of compounding may be regulated by adjustment of the shunt field resistance or by adjustment of a resistance connected in parallel with the series field winding.

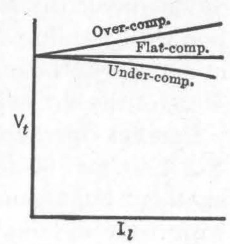


FIG. 59

Over-compounded generators are employed in connection with loads located at some distance from the generator and provide compensation for the potential drop in the transmission line. Flat compounded generators provide nearly constant potential at the terminals at any load. Under-com-

pounded generators are employed in general when compound generators are connected in parallel since the inherent distribution of load between such generators is more uniform if each generator possesses a drooping external characteristic.

All the above generators are called cumulative compound generators because the series winding in each acts in conjunction with and aids the shunt winding. In the differential compound generator the series winding is connected so that its mmf opposes that of the shunt. Such generators are often used in connection with electric arc welding where the resistance external to the generator frequently drops during the welding operation to very low values. The heavy current that would flow from the usual type of generator under these conditions is prevented in the differential compound generator by an immediate reduction in air gap flux and E_a by the high opposing mmf due to the reversed series field.

Parallel Operation of Electric Generators. Power plants are in general equipped with two or more generators. Frequently a single generator could not be obtained which would supply the entire load on the plant. The use of a single generator would, moreover, reduce the reliability of operation and no opportunity would be offered for making repairs without shutting down. Generators should always be selected as to number and size to operate at the least annual cost under the present and future load curve of the plant. The number of generators installed in a plant may also be increased to meet the demands of an increased load on the plant due to extensions or increased production. Unless special conditions favor the separate operation of each generator in connection with certain parts of the load, all generators will be connected in parallel to the main bus bars and each generator will supply its share of the entire load on the plant.

Parallel Operation of Shunt Generators. If a shunt generator, No. 1 in Fig. 60 for example, is supplying power to a load and another shunt generator, No. 2, is to be connected in parallel with it the terminal potentials of the two generators must first be adjusted to the same magnitude and polarity. The switch connecting the two generators may then be closed and the load may be distributed between the two generators by adjustment of the shunt field resistances or the armature speeds. The inherent distribution of load between the two generators will depend upon their external characteristics. If the external characteristics are not of similar form each generator will supply the same current to the load only at the terminal potential given by the intersec-

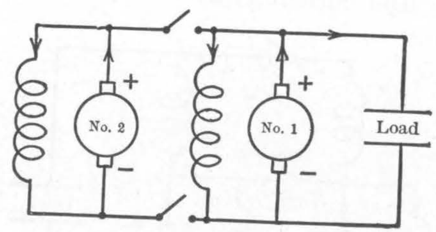


FIG. 60

tion of the characteristics as shown in Fig. 61. The characteristics must be identical in form if the load is to be distributed inherently between the two generators at all loads in the same proportion of the rated capacity of each generator.

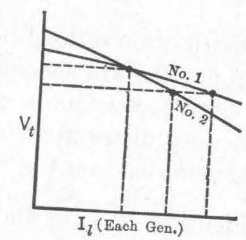


FIG. 61

Parallel Operation of Compound Generators. If a compound generator, No. 1 in Fig. 62, is supplying power to a load and another compound generator, No. 2, is to be connected in parallel with it the terminal potentials of the two generators must first be adjusted to the same magnitude and polarity. If switches S_2 and S_3 are now closed the two generators may operate satisfactorily in parallel but the operation with such connections is generally unstable. If the potential between c and d should drop for any reason below the potential between a and b, current may flow through the series field of No. 2 in the opposite direction to the normal series field current so that the series field mmf will oppose that of the shunt field. This reversal of current in the series field of No. 2 will then cause a cumulative reduction in the generated emf of No. 2 until No. 2 may finally be driven as a motor by No. 1. This action may overload No. 1 to the extent that its protective devices will disconnect it from the circuit. If No. 2 is of insufficient capacity to supply the load it will also be disconnected from the load and the system will be without a source of power.

The instability of operation just described may be eliminated by joining b and d in Fig. 62 with a low-resistance connection called the equalizer. With such a connnection the potential between a and b must be the same as that between c and d, and the reversal of either series field current is made impossible. The inherent distribution of load between two compound generators connected in parallel will depend upon their external characteristics and the relative resistances of their series field windings. For proportionate distribution of load between the two generators for any general load on the system the external characteristics should be identical in form and $\frac{(I_l)_1}{(I_l)_2}$ must equal $\frac{(R_s)_2}{(R_s)_1}$, where I_l and R_s are the full load line current and series field resistance respectively of each generator. The distribution of load between the two generators may be regulated by adjustment of the resistance of the shunt fields, series fields, and sometimes the equalizer, or by adjustment of the armature speeds.

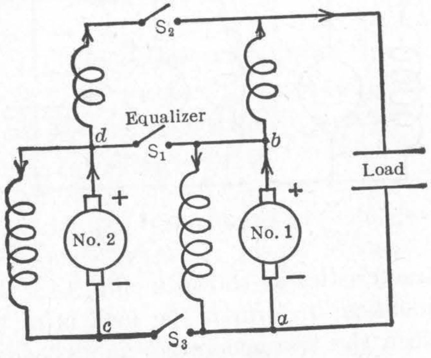


FIG. 62

Principles of Commutation. The currents flowing in the various parts of a generator armature adjacent to one of the brushes are shown in Fig. 63. I_x and I_y are the two currents which flow through two paths in the armature toward the positive brush. When the brush is centered on segment No. 1 of the commutator, the current I_y flows through the armature conductors connected between segments No. 1 and No. 2, joins I_x, and the combined current ($i_1 = I_x + I_y$) flows from a to b through the brush. When

the brush is centered (T seconds later) on segment No. 2, the current I_x flows through the armature conductors connected

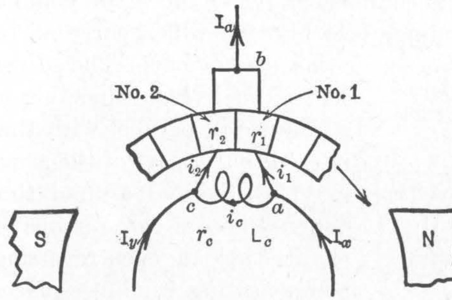


FIG. 63

between segments No. 1 and No. 2, joins I_y, and the combined current ($i_2 = I_x + I_y$) flows from c to b through the brush.

It is then evident that the current (i_c) flowing in the armature conductors connected between segments No. 1 and No. 2 reverses during the period of commutation as shown in Fig. 64. Sparkless commutation will be obtained if the current (i_1) flowing from segment No. 1 into the brush is zero at the instant when the brush breaks contact with segment No. 1. Since the connection between a and b through segment No. 1 contains no source of emf the current (i_1) flowing in this connection will be zero when v_{ab} is zero. The potential between a and b (taking the path acb), from 64, is given by $v_{ab} = +e_c - i_c r_c - i_2 r_2 - L_c \frac{di_c}{dt}$, where e_c, i_c, r_c, and L_c are the emf, current, resistance, and inductance, respectively, of the armature conductors connected between segments No. 1 and No. 2. Sparkless commutation will then be obtained if the emf (e_c) generated in the conductors undergoing commutation equals $i_c r_c + i_2 r_2 + L_c \frac{di_c}{dt}$ and acts from right to left in Fig. 63.

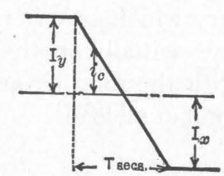


FIG. 64

Since no emf is generated in a coil located in the interpolar plane (unless the field is distorted no flux enters or leaves the armature at this point), sparkless commutation will be attained only by

establishing a small flux in the interpolar region of sufficient magnitude to establish an emf (e_c) of such value as to make v_{ab} zero. This is accomplished by auxiliary or commutating poles with series windings (see Fig. 65) which carry all or part of the armature current. The adjustment of current is made by connecting an adjustable resistance in parallel with the series windings so that a part of the armature current may be diverted around those windings. When motors are subjected to large changes in load, even reversing at full load, compensating windings placed in slots in the pole faces (Fig. 66) may also be employed to eliminate all distortion due to armature reaction and thus improve the effectiveness and adjustment of the auxiliary windings. It will be noted that the compensating winding is essentially another armature at rest which is connected in series with the rotating armature and produces an equal and opposite mmf at all loads.

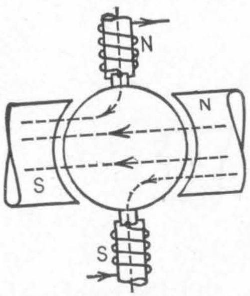
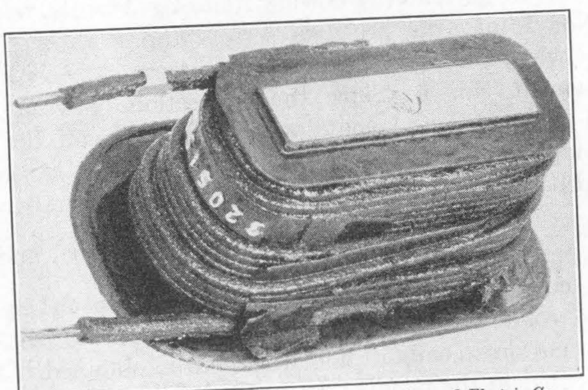


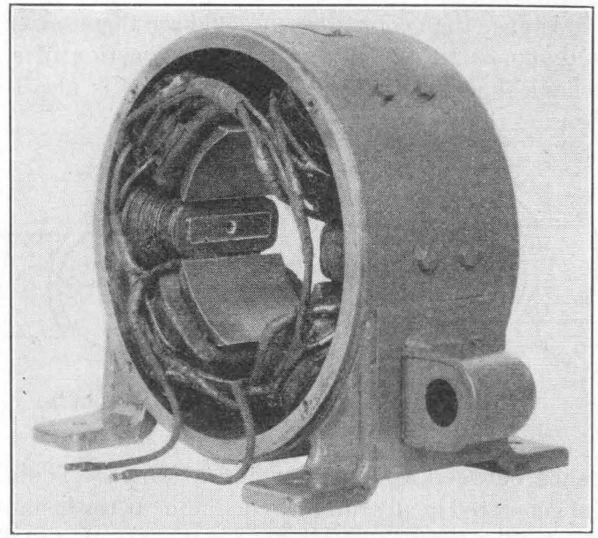
Fig. 65



General Electric Co.

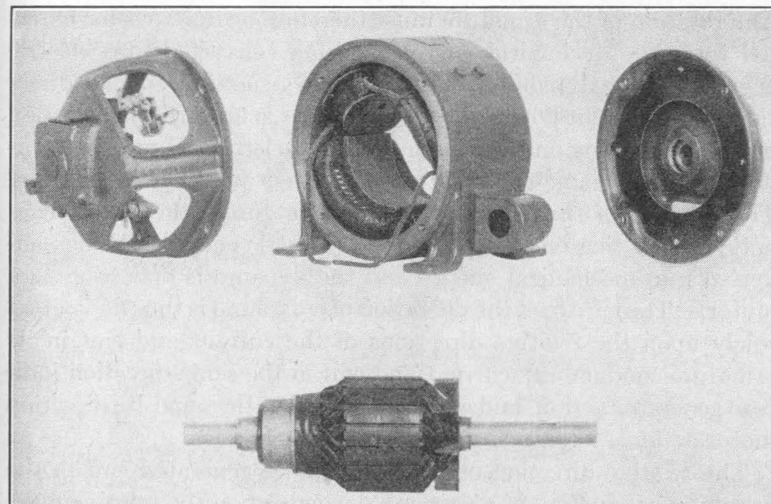
Commutating Pole and Winding for a Direct-current Motor.

The higher the resistance of the brush contact for a given potential between a and b the lower the current will be flowing from a to b through segment No. 1 (Fig. 63) just before the brush breaks



General Electric Co.

Field Assembly of a Direct-current Motor with Commutating Poles.



General Electric Co.

Direct-current Shunt Motor with Commutating Pole.

contact with segment No. 1. Carbon brushes present a higher contact resistance than copper brushes and are therefore employed on most dynamos to reduce the destructive action of sparking. The mechanical wear of a copper commutator is also less with carbon brushes than with copper brushes.

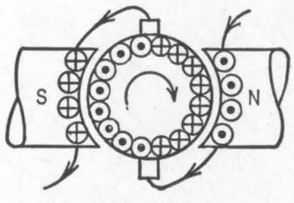


FIG. 66

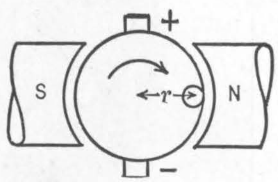


FIG. 67

Difference between a Generator and a Motor. The direction of the emf generated in an armature conductor at the instant shown in Fig. 67, by the right-hand rule, is downward. If the direction of the current flowing in this conductor is also downward, the direction of the force acting on the conductor, by the left-hand rule, is counterclockwise or opposite to the stated direction of rotation. The rotation of the armature must therefore be due to some external torque. Mechanical energy is being converted into electric energy and the dynamo is operating as a generator. If the direction of the current flowing in the conductor is upward the direction of the force acting on the conductor, by the left-hand rule, is clockwise or in the same direction as the stated direction of rotation. The rotation of the armature is therefore due to the electromagnetic force acting on the conductor. Electric energy is being converted into mechanical energy and the dynamo is operating as a motor. The nature of the operation of a dynamo is thus dependent solely upon the relative directions of the current and emf in its armature conductors; current and emf in the same direction indicate generator action, and current and emf in the opposite direction motor action.

The relative direction of the current and generated emf in the armature conductors of a dynamo depends upon the relative magnitude of the terminal potential and the generated emf. When the generated emf (E_a) of a dynamo is greater than the terminal potential (V_t) the armature current, from 14, is given by $I_a = \dfrac{E_a - V_t}{R_a}$. The current then flows in the same direction as the generated emf in each armature conductor and the dynamo operates as a generator. The terminal potential of a generator, from 6, is then given by

69 $$V_t = E_a - I_aR_a \text{ volts.}$$

When the generated emf (E_a) of a dynamo is less than the terminal potential (V_t), the armature current, from 14, is given by $I_a = \dfrac{V_t - E_a}{R_a}$. The current then flows in the opposite direction to the generated emf in each armature conductor and the dynamo operates as a motor. The terminal potential of a motor, from 6, is then given by

70 $$V_t = E_a + I_aR_a \text{ volts.}$$

Electromagnetic Torque of a Dynamo Armature. If the average flux density normal to the surface of an armature is B_{av} gausses, the armature current is I_a amperes, the flux-cutting length of each armature conductor is s centimeters and there are m paths in the armature between terminals, the average force acting upon each armature conductor, from 36, is given by $F_{av} = \dfrac{B_{av}I_as}{10\,m}$ dynes. If the distance from each conductor to the center of the armature (Fig. 67) is r centimeters, the average turning moment or torque produced by each conductor is given by $T_{av} = \dfrac{B_{av}I_asr}{10\,m}$ centimeter-dynes and the total torque due to Z conductors is given by $T = \dfrac{ZB_{av}I_asr}{10\,m}$ centimeter-dynes. Since the product of the number of poles (p) and the flux entering or leaving each pole (Φ) equals the surface area of the armature permeated by magnetic flux ($2\,\pi rs$) multiplied by the average flux density on the surface (B_{av}), $p\Phi = 2\,\pi rsB_{av}$ and $B_{av}sr = \dfrac{p\Phi}{2\,\pi}$. Substituting $\dfrac{p\Phi}{2\,\pi}$ for $B_{av}sr$ and converting the torque units into pound-feet, the electromagnetic

torque of a dynamo is given by

71 $$T = \frac{1.175\, Z I_a p \Phi}{m \times 10^9} \text{ pound-feet.}$$

In a generator the driving torque must exceed the value given by 71 and in a motor the torque developed at the pulley will be less than the value given by 71, the difference in each case being the torque associated with the rotational losses of a dynamo (discussed in detail on page 79).

The Speed-torque Characteristic of a Motor. Although the speed of a generator armature is fixed by the speed of the prime mover that drives it, the speed of a motor armature depends upon the electric and magnetic conditions within the armature and the nature of the mechanical load. The electromagnetic torque developed by a motor, from 71, may be indicated by $T = K_1 \Phi I_a$ pound-feet, where $K_1 = \frac{1.175\, Zp}{m \times 10^9}$. The armature current, from 14, is given by $I_a = \frac{V_t - E_a}{R_a}$ and, since $E_a = K_2 \Phi S$ where $K_2 = \frac{Zp}{6\, m \times 10^9}$, from 68, $I_a = \frac{V_t - K_2 \Phi S}{R_a}$. Hence the electromagnetic torque developed by a motor when the armature speed is S revolutions per minute is given by

72 $$T = \frac{K_1 \Phi}{R_a}(V_t - K_2 \Phi S) \text{ pound-feet.}$$

The electromagnetic torque is evidently a maximum at standstill unless the flux for some reason decreases with the speed. The actual standstill torque will be less than that indicated by 72 because resistance (R) must be connected in series with the armature at standstill so that $I_a = \frac{V_t}{R_a + R}$ will not greatly exceed the armature current rating of the motor.

Since the speed of any motor is the consequence of the electromagnetic torque the converse of 72 will indicate more clearly the factors upon which the speed of any motor depends

73 $$S = \frac{1}{K_2 \Phi}\left(V_t - \frac{T R_a}{K_1 \Phi}\right) \text{ rpm.}$$

When the electromagnetic torque is small (as at no load) the speed is a function principally of the terminal potential and air-gap flux. If the flux is very low the speed will be very high. The electromagnetic torque (T) in 73 at all times equals the torque (T_r) required to turn itself over plus the torque (T_l) required to

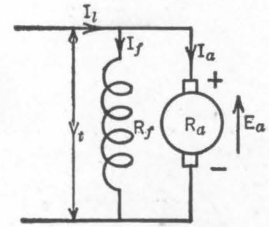


Fig. 68

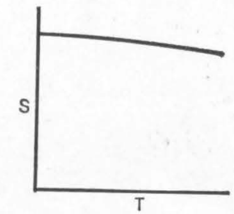


Fig. 69

turn over the machine driven by the motor. When any machine is driven by a motor the speed will then rise until $T = T_r + T_l$ at that speed. Although the armature resistance (R_a) is fixed this factor may be increased by connecting external resistance in series with it to reduce the speed.

The Shunt Motor. The shunt field current of a shunt motor is supplied from the line as shown in Fig. 68. Since the terminal potential (V_t) and the shunt field resistance (R_f) are in general constant the shunt field current (I_f), given by $I_f = \frac{V_t}{R_f}$, will also be constant. The air-gap flux of a shunt motor will then be sensibly constant, changing slightly with the armature reaction. The flux (Φ) in 73 being assumed constant the speed of a shunt motor may be indicated by $S = A - BT$ and may be represented graphically, within the range of current rating, by the curve shown in Fig. 69. Since the speed decreases slightly as the torque increases the shunt motor is employed in most systems of electric drive which require variable torque at sensibly constant speed.

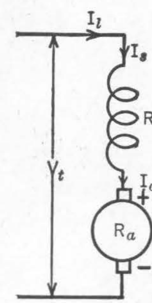
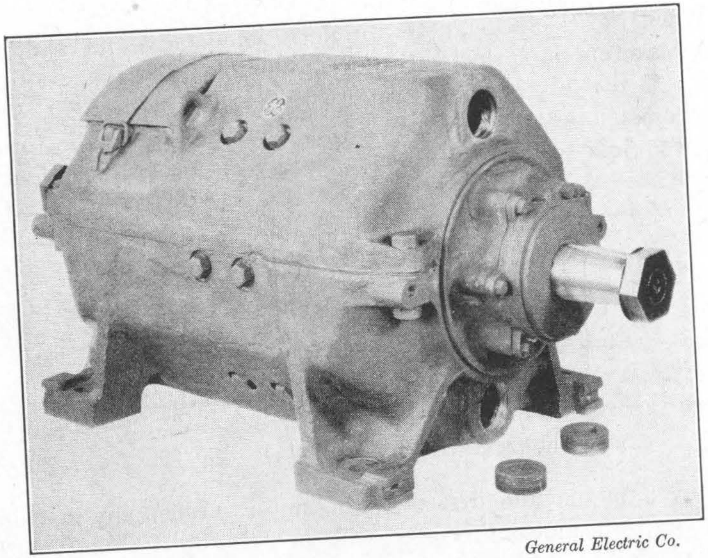


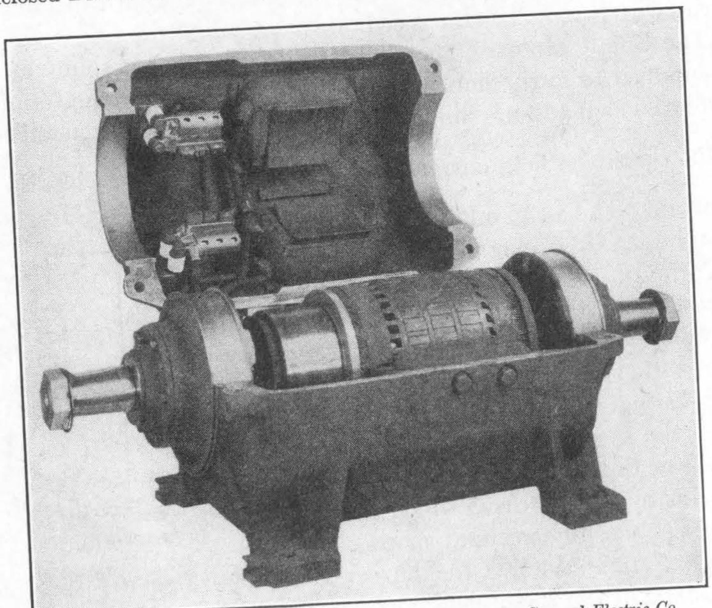
Fig. 70

The Series Motor. In the series motor (Fig. 70) the line current (I_l), the series field current (I_s) (if the series field is not shunted), and the armature current (I_a) are the same. The air-



General Electric Co.

Enclosed Direct-current Motor with Tapped Holes for Forced Ventilation.



General Electric Co.

Direct-current Series Motor.

gap flux will then vary with the line current (I_l) in the same manner as the air-gap flux (or generated emf) varies with the shunt field current in Fig. 49. If it is assumed, however, that the air-gap flux is directly proportional to the armature current, $T = K_1\Phi I_a$ may be converted as an approximation into $T = K_3\Phi^2$. Then by substituting $\Phi = \sqrt{\dfrac{T}{K_3}}$ in 73, we have $S = \dfrac{\sqrt{K_3}V_t}{K_2\sqrt{T}} - \dfrac{TR_aK_3}{K_1K_2T} = \dfrac{C}{\sqrt{T}} - D$. The D constant is in general small compared with C. The speed of a series motor will then be approximately inversely proportional to the square root of the torque as shown in Fig. 71. If the no load losses are small the no load torque will be small and the no load speed may produce excessive centrifugal stresses in the armature. The operation of series motors of more than one horsepower capacity at no load is therefore inadvisable. Since the torque increases as the speed decreases the series motor is best adapted to applications of the electric drive which require light torque at high speed and heavy torque at low speed, and which never allow the motor to operate at no load. Street cars are invariably driven by series motors for this reason.

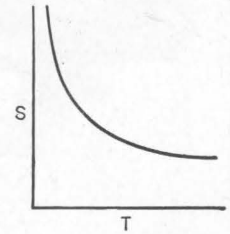
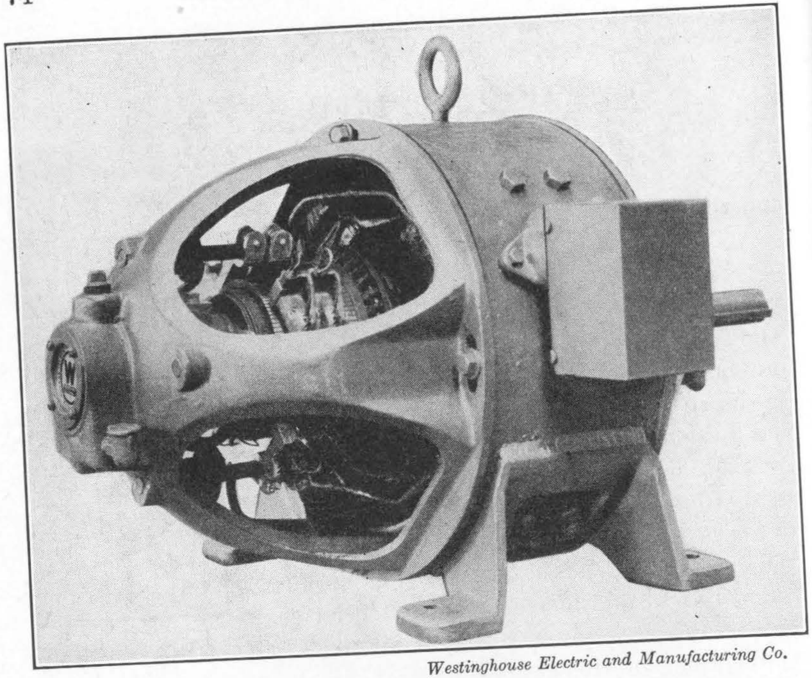


FIG. 71

The Compound Motor. Motors having both shunt and series field windings, called compound motors, possess speed-torque characteristics which may prove more desirable than those of the shunt or series motors in certain applications. Two types of compound motor may be used: the cumulative compound and the differential compound.

In the cumulative compound motor (Fig. 72) the shunt and series mmf's act in conjunction. The speed-torque characteristic (Fig. 73) will lie between the typical shunt and series characteristics and will depend upon the relative magnitude of the shunt and series mmf's. It will be noted that the cumulative compound motor has a definite (safe) no load speed and resembles the shunt motor in this respect but operates at lower speed than the shunt motor at higher values of the torque. The cumulative compound motor is therefore employed in electric drives which



Westinghouse Electric and Manufacturing Co.

Direct-current Motor containing Shunt, Series, and Commutating Field Coils.

require a definite no load speed and a lower speed than would be furnished by the shunt motor under heavy torque.

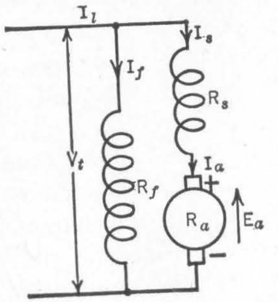


FIG. 72

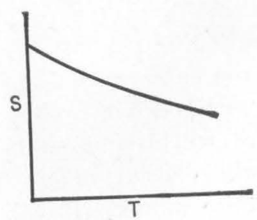


FIG. 73

In the differential compound motor shown in Fig. 74 the shunt and series field mmf's act in opposition. The speed-torque characteristic may be represented typically by the curve shown in Fig. 75.

The no load speed is definite as in the shunt and cumulative compound motor. An increase of load strengthens the series field mmf (which opposes the constant shunt field mmf) and decreases the air-gap flux. The generated emf ($K_2\Phi S$) being sensibly constant, the speed must increase. Since an increased speed will in general increase the reactive torque of the load, the speed will

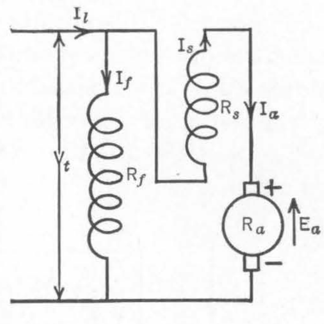


FIG. 74

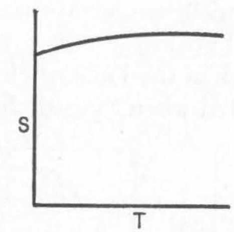


FIG. 75

increase consecutively, resulting in an overload. The starting torque is also low (it may be negative and start the motor in the wrong direction) since the opposing series field under starting conditions may have a mmf equal to or greater than that of the shunt field. A differential compound motor with very few series turns may operate at sensibly constant speed but a shunt motor will serve nearly as well for this purpose and possesses none of the disadvantages of the differential compound motor.

The Control of Starting Current in a Motor. The current flowing in the armature of a motor connected directly to the line at standstill is given, from 14, by $I_a = \dfrac{V_t}{R_a}$ for a shunt motor and by $I_a = \dfrac{V_t}{R_a + R_s}$ for a series or a long-shunt compound motor. In most motors this current would be at least ten times greater than the rated armature current of the motor at full load. In a motor thus connected directly to the line the armature winding and the brush contacts would be heated excessively, the armature winding would be subjected to excessive mechanical stresses, and the heavy

current drawn from the source of power supply would blow fuses or open circuit breakers, reduce the terminal potential and speed of other motors and dim the electric lamps on the same circuit.

Before a motor is connected to the line a resistance (R) should therefore be connected in series with the armature so that the initial current given by $I_a = \dfrac{V_t}{R_a + R}$ or $\dfrac{V_t}{R_a + R_s + R}$ will not greatly exceed the rated armature current of the motor at full load. The various types of starting box employed for this purpose contain some arrangement for decreasing the resistance connected in series with the armature as the motor comes up to speed and in general provide for an automatic reconnection of the series resistance when the line switch is opened so that the armature will be protected when the switch is closed again.

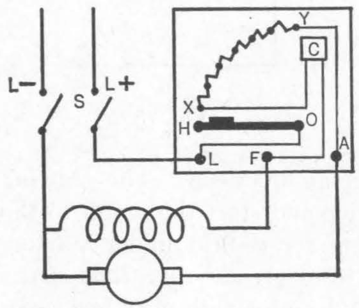


FIG. 76

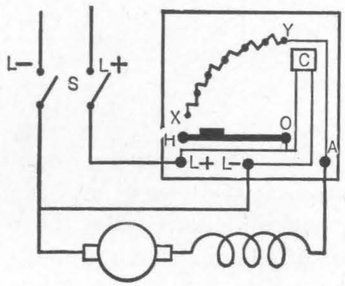


FIG. 77

A common three-point type of shunt motor starting box is shown in Fig. 76. After closing the line switch (S), the starting handle (H) is moved toward the right. The resistance (XY) in the starting box connected in series with the armature is thus gradually reduced to zero as the motor comes up to speed. Current also flows through the starting handle to X and then through a small electromagnet (C) on the face of the starting box to the shunt field. The resistance removed from the armature circuit is thus transferred to the field circuit during the starting period so that the initial field current may exceed the normal field current and provide increased starting torque. When the starting handle makes contact with Y (the motor is then running at rated speed with all starting resistance disconnected) the handle is held in that position by the magnetic attraction of the electromagnet (C). When the line switch is opened the current in the electromagnet (C) is interrupted and a helical spring at O returns the starting handle to the original starting position.

A common type of series motor starting box is shown in Fig. 77. The construction and operation are the same as in the shunt motor starting box except that the electromagnet (C) of high resistance wire is connected across the line (from $L+$ to $L-$). The opening of the line switch interrupts the current in the electromagnet (C) and the helical spring at O returns the starting handle to the original starting position.

Adjustment of the Speed of a Motor. Since the speed of any motor is maintained by its electromagnetic torque a momentary change in the electromagnetic torque is followed by a similar change in speed. The electromagnetic torque, from 72, being given by $T = \dfrac{K_1\Phi}{R_a}(V_t - K_2\Phi S)$ the torque and hence the speed of any motor must depend (other factors remaining constant) directly upon V_t and inversely upon R_a. The speed of any motor may then be increased by increasing V_t or by decreasing a resistance in series with R_a if the flux (Φ) is maintained constant.

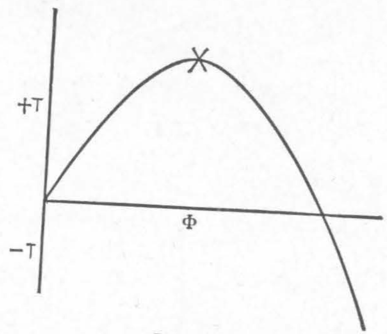


FIG. 78

The formula (72) for the torque may be rewritten, $T = \dfrac{K_1}{R_a}(V_t\Phi - K_2\Phi^2 S)$ and with other factors held constant the torque-flux curve is represented by Fig. 78. It will be seen that an increase in Φ from zero increases T up to the point (X). There-

after an increase in Φ decreases T to zero. A further increase in Φ reverses T and the motor may then operate only as a generator. The first derivative of T with respect to Φ equated to zero, $\frac{dT}{d\Phi} = \frac{K_1}{R_a}(V_t - 2\,K_2\Phi S) = 0$, indicates that at the point (X), $V_t = 2\,K_2\Phi S = 2\,E_a$. It is thus demonstrated that when E_a is less than $\frac{V_t}{2}$, an increase in Φ increases T and S, but if E_a is greater than $\frac{V_t}{2}$, an increase in Φ decreases T and S. Since E_a in the ordinary motor nearly equals V_t the speed is increased by reducing the flux. This may be accomplished in a shunt motor by increasing the shunt field resistance and in a series motor by decreasing the resistance of a shunt connected in parallel with the series field winding.

The methods of adjusting the speed of a motor may be summarized as follows:

Increase	Increase	Decrease
Terminal potential	Speed	.....
Armature resistance	.....	Speed
Air-gap flux $\left(E_a > \frac{V_t}{2}\right)$	.....	Speed
Air-gap flux $\left(E_a < \frac{V_t}{2}\right)$	Speed	.....

If two or more factors are changed simultaneously the resulting change in speed will depend upon the magnitude of each effect. In the shunt motor, for example, an increase of V_t will also cause an increase of Φ. If $E_a > \frac{V_t}{2}$ the two effects will be in opposition and the amount of speed increase will depend upon the flux density in the magnetic circuit, the increase of speed for a given increase of V_t being greater when the magnetic circuit is saturated.

The speed change due to any number of changes in the operating conditions of a motor may be determined by equating ratios of

E_a in 70 and 68 under the two operating conditions as follows:

74
$$\frac{(V_t - I_aR_a)_1}{(V_t - I_aR_a)_2} = \frac{\left(\frac{p\Phi ZS}{m}\right)_1}{\left(\frac{p\Phi ZS}{m}\right)_2}.$$

A 4-pole shunt motor, for example, has an armature with a lap winding of 400 conductors, and has a resistance between brushes of 0.5 ohm. When operated on a 230-volt line with an armature current of 20 amperes, the speed with a certain air-gap flux is 1500 rpm. If the armature is rewound with a wave winding of 300 conductors and has a resistance between brushes of 0.3 ohm, at what speed would this motor operate on a 115-volt line with an armature current of 10 amperes if the previous air-gap flux is increased 10 per cent? Substituting in 74 the speed is found to be 463 rpm.

The Power Losses in a Dynamo. The power losses in a dynamo are usually classified as (1) copper losses and (2) rotational losses (frequently called the stray power). The copper losses (the power converted into heat in the shunt field, series field, and armature windings) are determined as follows:

75 Shunt field $P_f = V_fI_f = I_f^2R_f = \frac{V_f^2}{R_f}$ watts,

76 Series field $P_s = I_s^2R_s$ watts,

77 Armature $P_a = I_a^2R_a$ watts.

The rotational losses include (1) friction losses in the bearings and at the brushes, (2) windage loss due to the motion imparted to the surrounding air by the rotating armature, (3) hysteresis loss (see page 32) due to the reversing magnetism in the rotating armature core and (4) eddy-current loss due to the heating effect of currents circulating in the armature core.

Reduction of the Losses in a Dynamo. The copper losses depend upon the square of the current and the resistance of the various windings. Since the ampere turns required in the field windings depend upon the reluctance of the magnetic circuit the field copper losses will depend upon the cross-sectional area of the magnetic circuit. The reduction of the copper losses (since the

currents in the various windings of a given dynamo are sensibly fixed) may be accomplished principally by increasing the weight of copper and iron in the respective electric and magnetic circuits. Increasing the weight of the copper decreases the resistance of the respective windings, and increasing the weight of the iron reduces the reluctance of the magnetic circuit and, in consequence, the number of ampere turns required to produce the required flux. Copper loss reduction is therefore limited by the desired weight and cost of the dynamo and by the desired magnitude of the rotational losses which increase in general as the weight of the dynamo increases.

With reference to the rotational losses, the friction loss depends principally upon the speed, the condition of the bearings and the commutator, the lubrication, and the brush pressure. The windage loss depends upon the speed, the surface irregularities of the armature, and the nature of the armature enclosure. Since the circulation of air around the armature assists in cooling the various windings and the armature core no attempt is made to reduce the windage loss. Fan blades are frequently attached to the armature to augment the circulation of air and increase the rated capacity of the dynamo.

The hysteresis loss may be computed with certain assumptions by

78 $$P_h = \frac{\eta p S V B_m^{1.6}}{12 \times 10^8} \text{ watts,}$$

where $\eta = 0.004$ for ordinary sheet iron and 0.001 for the best annealed sheet iron, p = the number of poles, S = the speed in rpm, V = the volume of the armature core in cubic centimeters, and B_m = the average maximum flux density in the armature core in gausses. The eddy-current loss may also be computed with certain assumptions by

79 $$P_e = \frac{V\,(tpSB_m)^2}{87.8\,\rho \times 10^8} \text{ watts,}$$

where t = the thickness of the laminations in centimeters and ρ = the resistivity of the iron in ohms per centimeter cube. All other quantities are described under hysteresis loss. If the armature core were solid the emf's generated in the rotating core

would cause currents to flow in the iron as shown in Fig. 79. By constructing the core of iron sheets (called laminations) insulated from each other electrically as shown in Fig. 80 the ratio of the

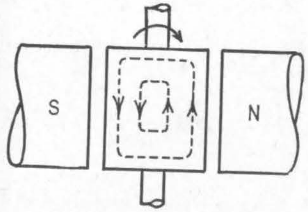


FIG. 79

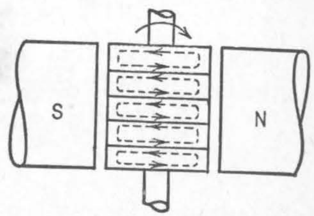


FIG. 80

emf to the resistance in each lamination is reduced and the eddy-current loss is materially diminished. The laminations are punched from soft sheet iron, 0.015 inch or more in thickness, and are insulated by the natural surface oxide or by a coat of varnish.

Determination of the Rotational Losses in a Dynamo. The rotational losses are usually determined experimentally by operating the dynamo as a shunt motor at no load, as in Fig. 81. The input to the armature $(V_t I_a)$ minus the armature copper loss $(I_a^2 R_a)$ minus the rotational losses (P_r) equals zero or $V_t I_a - I_a^2 R_a - P_r = 0$ and

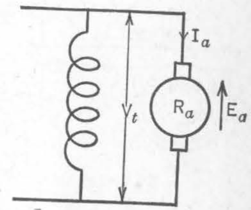


FIG. 81

80 $$P_r = V_t I_a - I_a^2 R_a \text{ watts.}$$

Since the rotational losses depend upon the speed and the flux density the rotational losses corresponding to any stated load are determined by operating the motor at no load at the same speed and flux density as at the stated load. If the mechanical output (P_o) of a motor operated under load may be measured accurately the rotational losses may be determined by

81 $$P_r = V_t I_a - I_a^2 R_a - P_o \text{ watts.}$$

The Efficiency of a Dynamo. The efficiency of a generator or a motor equals the ratio of the power output to the power input. The efficiency of a generator is then given by the ratio of the power

output to the sum of the power output and the losses. Hence the efficiency of a generator is given by

82 $$\eta_g = \frac{V_t I_l}{V_t I_l + V_f I_f + I_s^2 R_s + I_a^2 R_a + P_r}.$$

The efficiency of a motor is given by the ratio of the power input minus the losses to the power input or

83 $$\eta_m = \frac{V_t I_l - V_f I_f - I_s^2 R_s - I_a^2 R_a - P_r}{V_t I_l}.$$

If the output of a motor is measured by a Prony brake, as in Fig. 82, then $P_o = \frac{2\pi\, dSF}{33{,}000}$ horsepower, measuring d in feet, F in pounds, and S in revolutions per minute. Substituting T, the torque in pound-feet, for dF the power output is given by

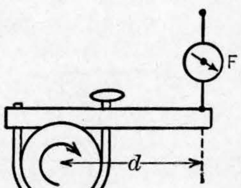


FIG. 82

84 $$P_o = 1.903\, ST \times 10^{-4} \text{ horsepower},$$

85 $$P_o = 0.1420\, ST \text{ watts}.$$

The efficiency of a motor is then given by

86 $$\eta_m = \frac{0.1420\, ST}{V_t I_l}.$$

Characteristic Curves of a Motor. The principal operating characteristics of a motor (speed, efficiency, torque, and line cur-

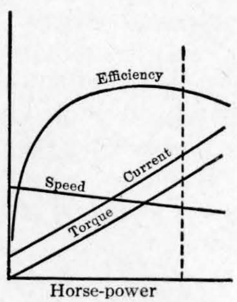


FIG. 83

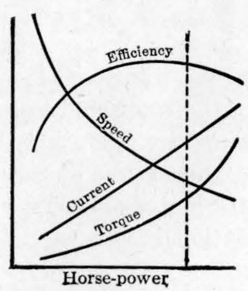


FIG. 84

rent) are usually plotted with reference to the output in horsepower and are called the characteristic curves of a motor. Typi-

cal characteristic curves of a shunt motor are shown in Fig. 83, and of a series motor in Fig. 84. Full load values for each quantity are indicated by the intersection of the vertical dotted line.

Practice problems with answers for Chapter IV will be found on pages 244 to 256.

CHAPTER V

DIRECT-CURRENT MEASUREMENTS

Legal Units of Electrical Measure. An Act of Congress (1894) following the recommendation of the International Electrical Congress of 1893 established the following legal units of resistance, current, and emf in the United States.

The Ohm. The resistance offered to an unvarying electric current by a column of mercury 14.4521 grams in mass, of constant cross-sectional area, and of the length 106.3 centimeters at the temperature of melting ice.

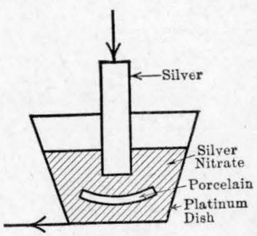


FIG. 85

The Ampere. The unvarying current which, when passed through a solution of nitrate of silver in water in accordance with standard specifications, deposits silver at the rate of 0.001118 gram per second.

The Volt. The emf that, steadily applied to a conductor whose resistance is 1 ohm, will produce a current of 1 ampere.

The same units have been adopted by most other countries and are therefore called international units. The device in which current is measured by the deposition of silver is called a silver voltameter (Fig. 85).

Secondary Reference Standards. Since the mercury ohm and the silver voltameter have proved inconvenient for frequent use as reference standards the Bureau of Standards has prepared and maintained secondary reference standards of resistance and emf. The secondary standards of resistance are sealed wire resistances called N. B. S. (National Bureau of Standards) standard resistors (Fig. 86), which are compared at infrequent intervals with the mercury ohm. The secondary standard of emf is the saturated Weston cell (Fig. 87) which is calibrated at infrequent intervals by

the silver voltameter and a standard resistance. The emf of this cell at 20 C is 1.0183 volts. When used as reference standards the secondary standards of resistance and emf are compared respectively in groups, the average value of the group in each case being adopted as the secondary standard.

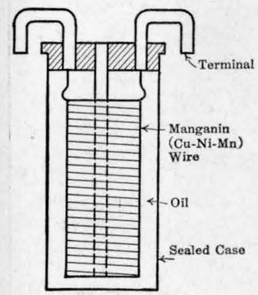


FIG. 86

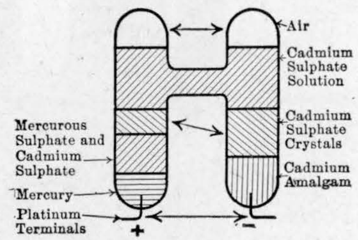
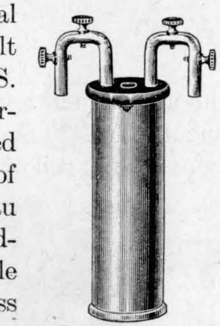


FIG. 87

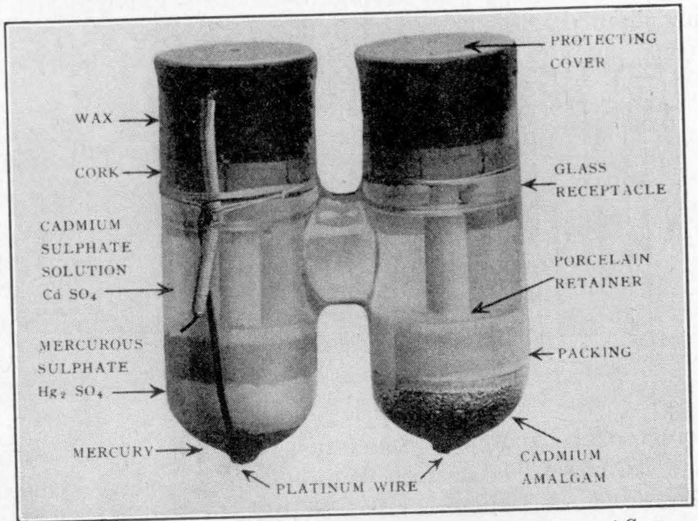
Commercial Laboratory Standards. The reference standards of the commercial laboratory resemble the secondary standards of the Bureau of Standards but may differ in certain elements of construction. A common form of commercial standard resistor, called the Reichsanstalt model, is a wire standard but unlike the N. B. S. model is not hermetically sealed. The commercial standard cell is usually the unsaturated Weston cell, the cell used by the Bureau of Standards being saturated; that is, the Bureau of Standards cell contains an excess of cadmium sulphate crystals. While not as reliable as the saturated cell, the unsaturated cell is less affected by changes of temperature. The commercial or tertiary reference standards are compared occasionally with groups of secondary reference standards at the Bureau of Standards so that any changes in them may be detected.



Leeds and Northrup Co.
Ten-ohm N.B.S. Standard Resistor.

Ammeters and Voltmeters. Portable or switchboard instruments designed for the measurement of current or potential usually consist of a light rectangular coil of fine copper wire wound upon an aluminum frame, pivoted in jeweled bearings, and located in the

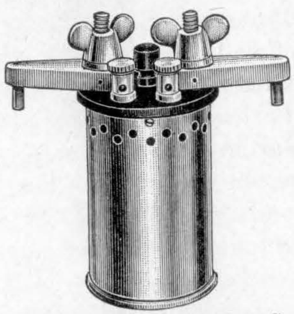
annular space between a soft iron core and the pole faces of a permanent magnet as shown in Fig. 88. Electrical connections with the coil are made through two spiral springs which also resist



Weston Electrical Instrument Corp.

Weston Standard Cell.

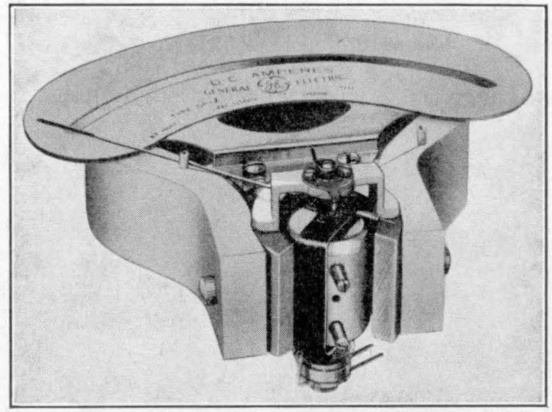
the angular motion of the coil with a torque proportional to the angular twist. Since the torque acting upon the coil is proportional to the coil current the magnitude of the current is indicated by the motion of a light tubular pointer over a calibrated scale.



Leeds and Northrup Co.

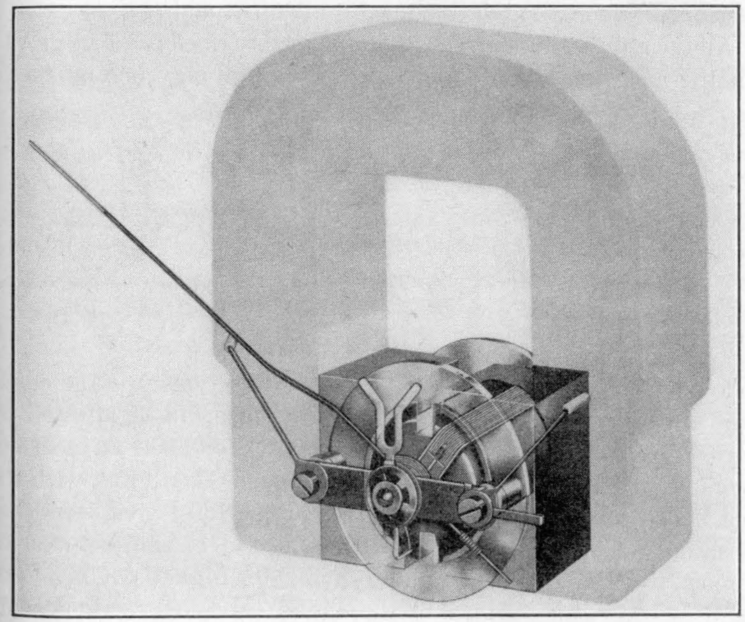
One Thousandth-ohm Reichsanstalt Standard Resistor.

The instrument shown in Fig. 88 may be employed to measure a current not greater than 0.025 ampere and a potential not greater than 1.5 volts (approx.), the potential being determined indirectly by the product of the coil current and the coil resistance. To measure a current greater than 0.025 ampere the coil is shunted as shown in Fig. 89. If the coil resistance is represented by R_c and



General Electric Co.

Construction of Moving-coil Type Direct-current Ammeter.



Weston Electrical Instrument Corp.

Weston Portable Milliammeter.

the shunt resistance by R_s the ammeter resistance is given by $R_a = \frac{R_c R_s}{R_c + R_s}$. The ammeter current is then given by $I_a = \frac{I_c R_c}{R_a}$, the range of the instrument being dependent upon the relative magnitude of R_c and R_a. To measure a potential greater than 1.5 volts the coil is connected in series with a high resistance as shown in Fig. 90. If the resistance of the coil is represented by R_c and the added series resistance by R_e the resistance of the voltmeter is given by $R_v = R_e + R_c$. The potential (V_v) across the voltmeter in terms of the potential (V_c) across the coil is then given by $V_v = \frac{V_c R_v}{R_c}$, the range of the instrument being dependent upon the relative magnitude of R_v and R_c.

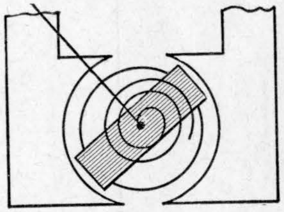


FIG. 88

All the alternating-current instruments described in Chapter VII for the measurement of current and potential may be applied to

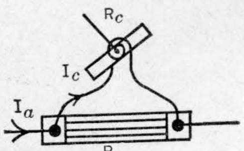


FIG. 89

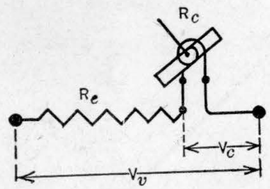
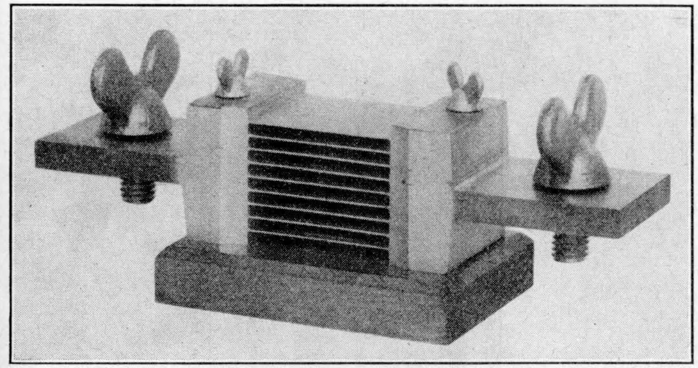


FIG. 90

direct-current circuits but with certain restrictions in some cases. The electrodynamometer and iron vane types will be affected by terrestrial magnetism or other outside sources and give an incorrect reading unless the average of two readings is taken; first with the instrument in one position and second, turned 180 degrees from that position. When the iron vane type is used in a direct-current circuit, there is a tendency due to hysteresis for the reading to be high for decreasing values of the current and low for increasing values. The iron vane type is used extensively (the iron vane is sometimes polarized) for small instruments of low cost when high accuracy is not important.

The Wattmeter. The measurement of power in a direct-current circuit is seldom accomplished by a single instrument since the power may always be determined by the product of the voltmeter and ammeter readings. The dynamometer wattmeter



General Electric Co.

Direct-current Ammeter Shunt.

described on page 122 may be employed for this purpose whenever the use of a single instrument is found desirable. Its readings will also be affected by terrestrial magnetism but the actual power will be given by the average of two readings taken with the instrument in one position and then turned 180 degrees from that position, or first with one connection of the potential and current coils and second with both coils reversed.

The Watthour Meter. The instrument most commonly employed for measuring the energy supplied to any part of a direct-current circuit is the Thomson watthour meter shown in Fig. 91. The revolving element consists of a hollow spherical armature (A) with a commutator (C) and a metal disc (D), all mounted upon a shaft which turns on a jeweled bearing (B). The number of revolutions of the revolving element is registered by a series of dials (G) which are connected by gears to the shaft. Two field

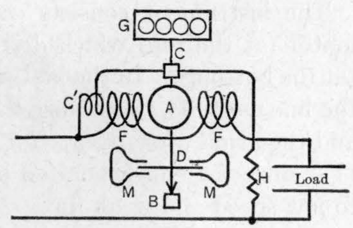
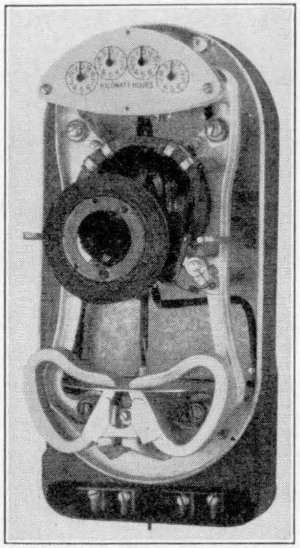


FIG. 91

coils (FF) are connected in series with the load under measurement, and the armature in series with a compensating coil (C') and a high resistance (H) is connected across the line. The metal disc (D) revolves between the pole faces of two or more permanent magnets (MM).



General Electric Co.

Direct-current Watthour Meter.

The instrument consists essentially of a direct-current shunt motor (at the top) which drives an alternating-current generator (at the bottom). In the motor the field flux (Φ_f) is proportional to the line current (I_l) because the magnetic circuit contains no iron, and the armature current (I_a) is proportional to the line potential (V_l) since the emf generated in the armature is very small owing to low speed and weak flux. The motor torque (T_M) is then proportional to V_lI_l or the power (P) supplied to the load, and $T_M = K_1P$. In the generator, since the magnetic flux passing through the rotating disc is constant, the emf (E) generated in the disc is proportional to the speed (S) of the disc. Since the resistance of the disc is constant for a given temperature the current (I) flowing in the disc is also proportional to the speed (S). The flux passing

through the disc being constant the generator torque (T_G) is then proportional to the speed (S), and $T_G = K_2S$.

If the friction of the bearing, commutator, and gears is neglected $T_M = T_G$ and $P = KS$. Since energy (W) equals the product of power (P) and time (t), $W = Pt = KSt$ and $W = KR$ where $R = St$ is the number of revolutions of the disc in time (t). With the proper gear connection the dials will then indicate directly the energy supplied to the load in a given time. The frictional torque of the revolving element being too large to be neglected, a compensating field coil (C') is provided to supply an additional torque which is independent of the load and equal to the frictional torque. Owing to the high resistance of the armature circuit the speed of the motor is directly proportional to the field flux as described on page 78.

Measurement of Resistance. Accurate measurement of resistance may be accomplished by some form of Wheatstone bridge as shown in Fig. 92. A battery (B) is connected to the terminals (ab) of a parallel connection containing three known adjustable resistances (R_1, R_2, and R_3), the unknown resistance (R_4), and a galvanometer (G) connected between c and d.

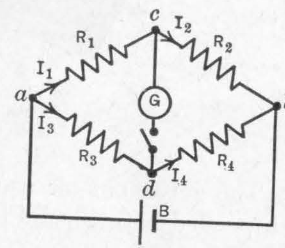
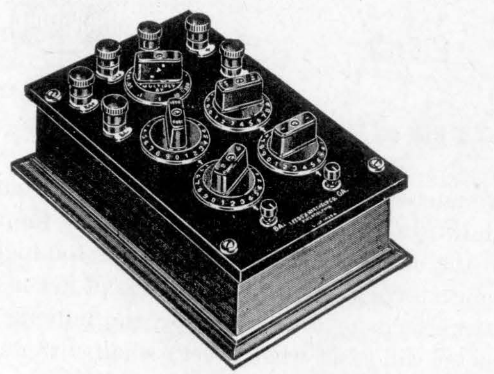
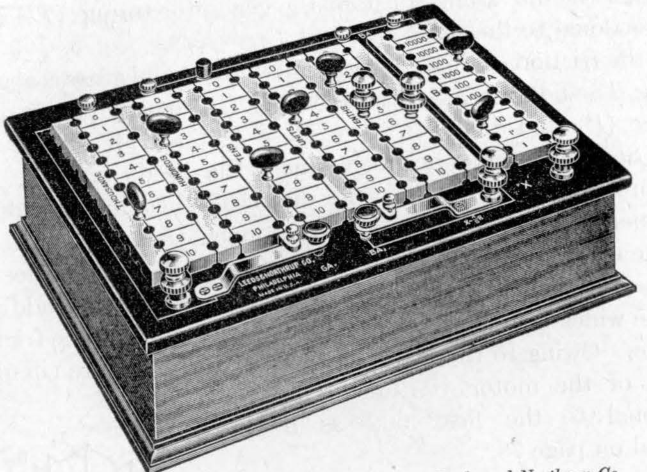


Fig. 92



Leeds and Northrup Co.

Dial-switch Wheatstone Bridge.



Leeds and Northrup Co.

Plug-type Wheatstone Bridge.

The galvanometer usually consists of a light coil of fine wire suspended between the poles of a permanent magnet as shown in Fig. 93. This type will respond to a current of the order of 10^{-12} ampere. When conditions demand a more sensitive instrument a

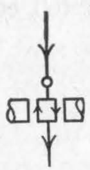


FIG. 93

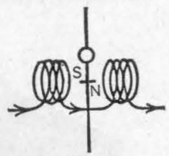
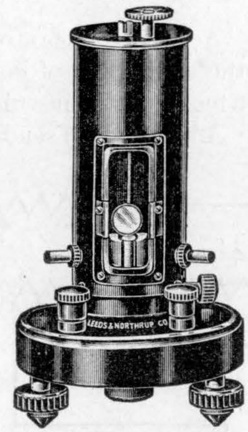


FIG. 94

small permanent magnet is suspended at the center of a coil of wire as shown in Fig. 94. The sensitivity of the moving magnet type is in the order of 10^{-16} ampere and is too high for most purposes because the galvanometer will be kept in constant motion by varying stray fields. In either case the moving element of the galvanometer will twist when a very small current is sent through the galvanometer coil. Evidence of a twist in the moving element is usually magnified by directing a beam of light upon a small

mirror attached to the moving element so that the reflected light may be viewed on a scale located at some distance from the galvanometer. The galvanometer in this way serves as a sensitive detector of an electric current.



Leeds and Northrup Co.

Moving Coil Galvanometer.

If no galvanometer deflection follows the closing of the galvanometer key in Fig. 92 the potential between c and d must be zero. Then $I_1 = I_2$, $I_3 = I_4$, $I_1R_1 = I_3R_3$, $I_2R_2 = I_4R_4$, $\dfrac{I_1R_1}{I_2R_2} = \dfrac{I_3R_3}{I_4R_4}$ and the ratio of the bridge resistances is given by

87 $$\frac{R_1}{R_2} = \frac{R_3}{R_4}.$$

The value of R_4 may thus be determined by adjusting R_1, R_2, and R_3 until there is no deflection of the galvanometer.

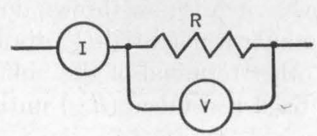


FIG. 95

A less accurate measurement of resistance may be made with a voltmeter and an ammeter connected as shown in Fig. 95. If the

current taken by the voltmeter is neglected $R = \frac{V}{I}$ ohms. If the current taken by the voltmeter of R_v ohms resistance is considered $R = \frac{VR_v}{IR_v - V}$ ohms.

The Potentiometer. Accurate laboratory measurements of potential and current, the calibration of instruments, etc., are in general accomplished by means of the instrument shown in Fig. 96 called a potentiometer. A battery (B) sends a current through an

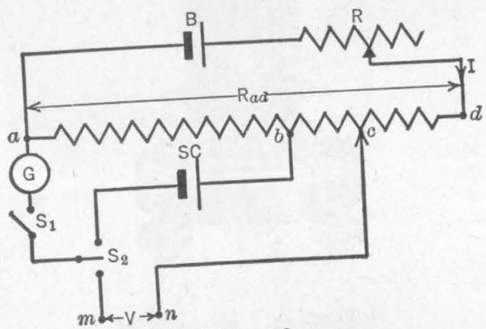
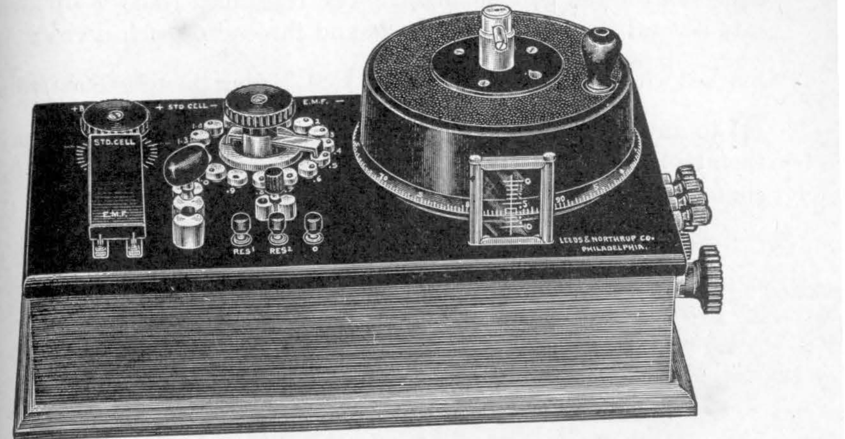


FIG. 96

adjustable resistance (R) and a fixed resistance (R_{ad}), the capacity of the battery being sufficient to maintain a steady current in the fixed resistance. One terminal of a standard cell (SC) is connected permanently to a definite point (b) in the fixed resistance (R_{ad}) and the other terminal may be connected through a double-throw switch (S_2), a galvanometer key (S_1), and a galvanometer (G) to the point (a). If the resistance (R) is adjusted until the galvanometer shows no deflection with the standard cell connected in the circuit IR_{ab} must equal E_{sc}, the emf of the standard cell; that is, V_{ab} equals 1.0183 volts (usually).

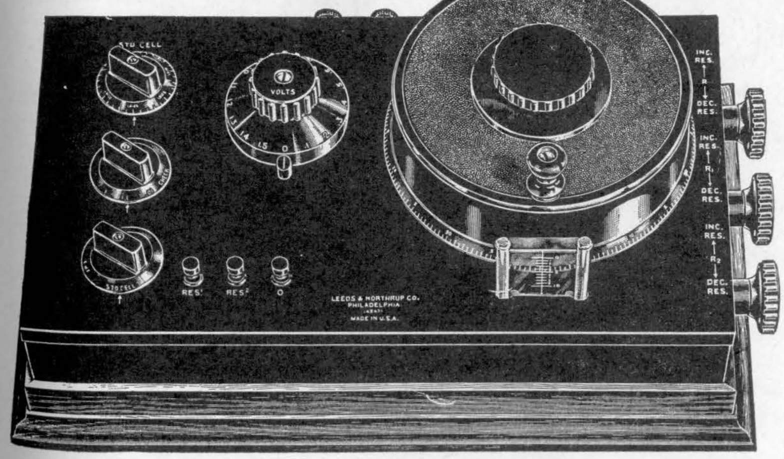
If the double-throw switch is now thrown downward connecting one terminal of an unknown potential (V) through the galvanometer to (a) and the other terminal of the unknown potential (V) is moved along the fixed resistance (R_{ad}) until the galvanometer shows no deflection, then V must equal V_{ac} or $V = 1.0183 \left(\frac{R_{ac}}{R_{ab}}\right)$.

The ratio $\left(\frac{R_{ad}}{R_{ab}}\right)$ is usually such as to make V_{ad} equal 1.61 volts



Leeds and Northrup Co.

Type K–1 Potentiometer.



Leeds and Northrup Co.

Type K–2 Potentiometer.

when the connection of the standard cell in circuit produces no deflection of the galvanometer. The resistance (R_{ad}) is divided into several thousand equal parts and the end of each division is marked with the value $1.0183\left(\frac{R_{ax}}{R_{ab}}\right)$, R_{ax} being the resistance from (a) to any point (x). The value of the unknown potential may then be read directly from the instrument at the point where the contact (c) gives no deflection of the galvanometer.

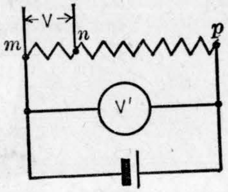


FIG. 97

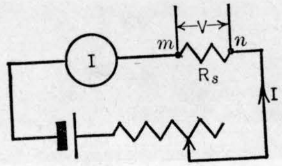


FIG. 98

Potentials higher than 1.61 volts may be measured by connecting a definite part of a high resistance (mp) between (m) and (n) as shown in Fig. 97. The unknown potential (V') then equals $V\left(\frac{R_{mp}}{R_{mn}}\right)$ and a voltmeter connected between (m) and (p) may be calibrated throughout its range. In measuring current with the potentiometer a standard resistor (R_s) is connected between (m) and (n) as shown in Fig. 98. The current flowing through the standard resistor is then given by $I = \frac{V}{R_s}$ and an ammeter connected in series with the standard resistor may be calibrated throughout its range.

Practice problems with answers for Chapter V will be found on pages 256 to 258.

CHAPTER VI

ALTERNATING-CURRENT CIRCUITS

Alternating Emf. The variation of the instantaneous emf generated in each armature conductor of a dynamo during one revolution of the armature depends upon the distribution of the flux density in the air gap as explained on page 47. A plot of the successive instantaneous values of the emf generated during the

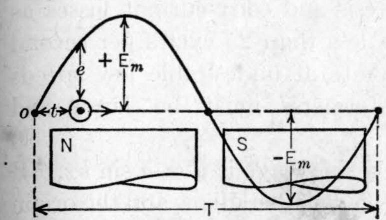


FIG. 99

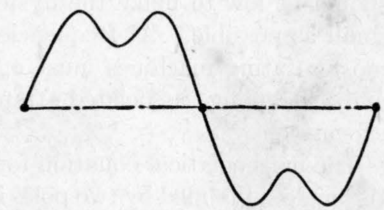


FIG. 100

passage of a conductor by two poles is called the wave form of the emf, a typical sinusoidal wave form of an alternating emf being shown in Fig. 99. A non-sinusoidal wave form like that shown in Fig. 100, for example, introduces higher frequency harmonics into the circuit as well as the fundamental. Eddy-current and hysteresis losses will be increased in all apparatus in the system and currents of audible frequency producing undesirable hums and whistles may be induced in adjacent communication circuits. In general a non-sinusoidal emf will be distorted in any circuit more than a sinusoidal emf. The mathematical analysis of alternating-current circuits is simpler when based upon the sinusoidal wave form.

Terminology of an Alternating Emf. A source of alternating emf is indicated by the symbol . A complete sequence of values of emf from zero to maximum positive ($+E_m$) to zero to maximum negative ($-E_m$) to zero (Fig. 99) is called the emf cycle.

The time in seconds taken by the emf to pass through one cycle is called the period (T) of the emf cycle. The number of emf cycles per second is called the frequency (f) of the emf cycles. The frequency then equals the reciprocal of the period or $f = \frac{1}{T}$ cycles per second. The frequency of the emf and current in most alternating-current systems is either 60 or 25 cycles per second, 60 cycles per second being employed generally in lighting circuits and 25 cycles per second in circuits supplying power to motors.

It is desirable in all electric lamps, particularly those of small size, operating with alternating current to keep the frequency of the current at a value high enough to eliminate objectionable flicker. In electrical machinery and in transformers the frequency should be low to make the hysteresis and eddy-current losses as small as possible. At frequencies less than 25 cycles per second most rotating machines must operate at undesirable low speeds and, including associated transformers, must be large and expensive.

The mathematical equation for a sine wave is $y = a \sin bx$. If the angle subtended by two poles is called 2π radians and the origin be located at o (Fig. 99), the angular distance of the conductor from the origin t seconds after leaving the origin will be $\frac{t}{T} \cdot 2\pi$ radians. Substituting e for y, E_m for a and $\frac{2\pi}{T} \cdot t$ for bx, the equation of the emf is given by $e = E_m \sin \frac{2\pi}{T} t$ or $e = E_m \sin 2\pi ft$. The product $(2\pi f)$ which represents the angular velocity of the conductor is usually indicated by ω. The mathematical equation for a sinusoidal emf is then given by

88 $$e = E_m \sin \omega t \text{ volts,}$$

where e is the emf in volts generated in the conductor t seconds after the emf is zero and is increasing toward the positive maximum, E_m is the maximum value of the emf in volts, and ω is the angular velocity of the conductor in electrical radians per second. Electrical radians equal trigonometric radians multiplied by the number of pairs of poles.

Difference in Phase. The wave forms of the two emf's generated in the two conductors shown in Fig. 101 will be identical since each conductor must pass through the same magnetic field. The emf generated in conductor No. 1 must differ from that generated in conductor No. 2 at the same instant since the two conductors do not pass through the same part of the magnetic field at the same instant. Corresponding values of emf are

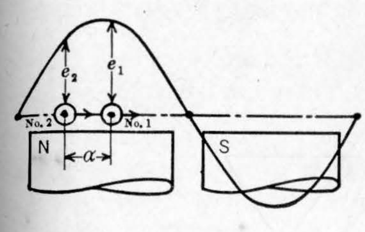


FIG. 101

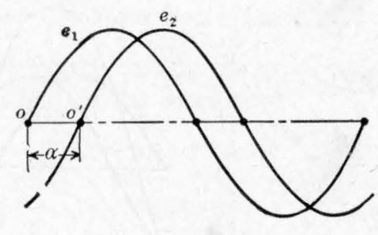


FIG. 102

generated later in conductor No. 2 than in conductor No. 1 and the two emf's are said to differ in phase by α degrees. The phase difference between e_1 and e_2 may be represented graphically as shown in Fig. 102 in which the two wave forms are displaced by the angle (α) between the two conductors. In the wave diagram a lagging emf by convention is displaced to the right and a leading emf to the left of the arbitrary axis of reference. Although the angle (ωt) in 88 is measured in radians a phase difference is usually expressed in degrees. The emf (e_2) in Fig. 102, for example, is said to lag the emf (e_1) by α degrees or the emf (e_1) is said to lead the emf (e_2) by α degrees. Phase difference may be indicated mathematically by referring each emf to the same origin. With the origin at o, $e_1 = E_{m1} \sin \omega t$ and $e_2 = E_{m2} \sin (\omega t - \alpha)$ and with the origin at o', $e_2 = E_{m2} \sin \omega t$ and $e_1 = E_{m1} \sin (\omega t + \alpha)$.

Addition of Sinusoidal Emf's. The two emf's (e_1 and e_2) in Fig. 102 may be added graphically by adding simultaneous ordinates as shown in Fig. 103. The resultant emf (e_0) will also be sinusoidal and will differ in phase from both e_1 and e_2. The same emf's expressed mathematically by

$$e_1 = E_{m1} \sin \omega t \quad \text{and} \quad e_2 = E_{m2} \sin (\omega t - \alpha)$$

may be added by applying the trigonometric formula for the sum of the sines of two angles multiplied by constants. The resultant emf is then given by

89 $$e_0 = \sqrt{(E_{m1} + E_{m2}\cos\alpha)^2 + (E_{m2}\sin\alpha)^2}\ \sin\left(\omega t - \tan^{-1}\frac{E_{m2}\sin\alpha}{E_{m1} + E_{m2}\cos\alpha}\right) \text{ volts.}$$

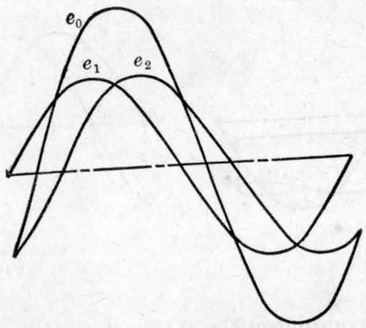


FIG. 103

The same result may be obtained in a simpler manner by representing each emf by a rotating vector as shown in Fig. 104, the rotation by convention being counterclockwise at an angular velocity of ω radians per second. E_{m1}, the maximum value of e_1, is drawn along the horizontal axis (the axis of reference) and E_{m2}, the maximum value of e_2, is drawn at an angle of α degrees in a clockwise direction from E_{m1} to indicate a phase lag of α degrees.

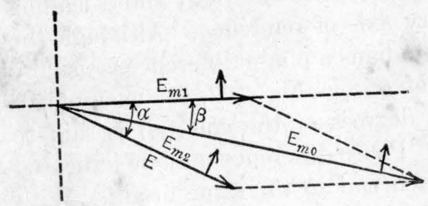


FIG. 104

The instantaneous emf in either case is given by the projection of each vector on the vertical axis. Since each vector rotates at the same speed the maximum value of their sum in accordance with the principle of vector addition is given by the diagonal (E_{m0}) of the completed parallelogram. The horizontal component of E_{m0} is $E_{m1} + E_{m2}\cos\alpha$ and the vertical component is $E_{m2}\sin\alpha$.

Then $E_{m0} = \sqrt{(E_{m1} + E_{m2}\cos\alpha)^2 + (E_{m2}\sin\alpha)^2}$. The phase angle ($\beta$) between e_0 and e_1 is given by $\tan^{-1}\dfrac{E_{m2}\sin\alpha}{E_{m1} + E_{m2}\cos\alpha}$ and the complete equation for the resultant emf is given by 89. It will be observed that any number of emf's may be added in the same manner by the vector method. If the summation of the horizontal components is indicated by ΣH and the summation of the vertical components by ΣV, $e_0 = \sqrt{(\Sigma H)^2 + (\Sigma V)^2}\ \sin\left(\omega t + \tan^{-1}\dfrac{\Sigma V}{\Sigma H}\right)$, the signs of the various components being fixed by the usual convention employed in the system of rectangular coördinates.

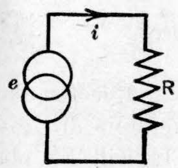


FIG. 105

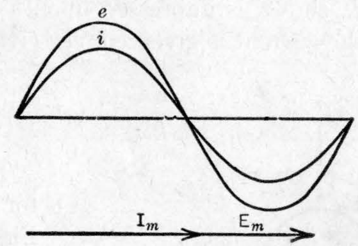


FIG. 106

Current Established in Resistance by a Sinusoidal Emf. Since the current (i) established in a resistance (R) by an emf (e) from 14 is given by $i = \dfrac{e}{R}$ for any value of e, the current established in a resistance (R) in Fig. 105 by a sinusoidal emf, $e = E_m \sin\omega t$, is given by

90 $$i = \frac{E_m}{R}\sin\omega t \text{ amperes.}$$

The wave and vector diagrams for a circuit containing resistance only are shown in Fig. 106. It will be observed that the current and emf are in phase and the maximum current (I_m) equals the maximum emf (E_m) divided by the resistance (R).

Current Established in Inductance by a Sinusoidal Emf. If an alternating current, $i_{cd} = I_m \sin\omega t$, is established in a circuit containing inductance only (Fig. 107) the emf induced in the

inductance by the alternating current, from 54, is given by

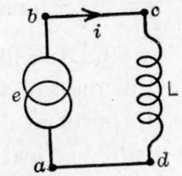


FIG. 107

$$e_{dc} = L\frac{di_{cd}}{dt}$$
$$= L\frac{d(I_m \sin \omega t)}{dt}$$
$$= L\omega I_m \cos \omega t$$
$$= L\omega I_m \sin (\omega t + 90°).$$

An emf, $e_{ab} = L\omega I_m \sin (\omega t + 90°)$, must then be impressed upon the circuit to maintain the current, $i_{cd} = I_m \sin \omega t$. If an emf, $e = E_m \sin \omega t$, is impressed upon a circuit containing inductance only the current is given conversely by

91 $$i = \frac{E_m}{L\omega} \sin (\omega t - 90°) \text{ amperes.}$$

The wave and vector diagrams for such a circuit are given in Fig. 108. It will be observed that the current lags the emf by 90 degrees and the maximum current (I_m) equals the maximum emf (E_m) divided by the product of the inductance (L) and the angular velocity (ω).

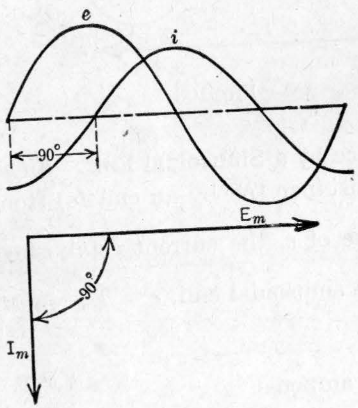


FIG. 108

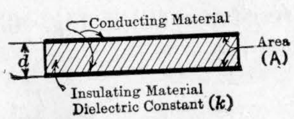


FIG. 109

The Capacitance of a Condenser. When two conducting materials are separated by an insulating material the combination is called a condenser (Fig. 109). When an emf is impressed upon a condenser containing a perfect insulator the current (i) flowing in the condenser equals the product of a constant (C) and

the rate of change of the impressed emf $\left(\frac{de}{dt}\right)$ or

92 $$i = C\frac{de}{dt} \text{ amperes.}$$

The constant (C) is called the capacitance of the condenser and when the current is measured in amperes and the rate of change of the emf in volts per second the capacitance (C) is measured in farads. The microfarad, a smaller unit of capacitance, equals one millionth of a farad. The capacitance of a condenser is proportional to (1) the area (A) of each of the adjacent surfaces of the conducting materials, (2) the dielectric constant (k) of the insulation between the conducting materials, and is inversely proportional to (3) the distance (d) between the conducting materials. The dielectric constants of various materials compared with air ($k = 1$) are given on page 222. When several condensers are connected in parallel the equivalent capacitance equals the sum of the individual capacitances or

93 $$C = C_1 + C_2 + C_3 \text{ farads.}$$

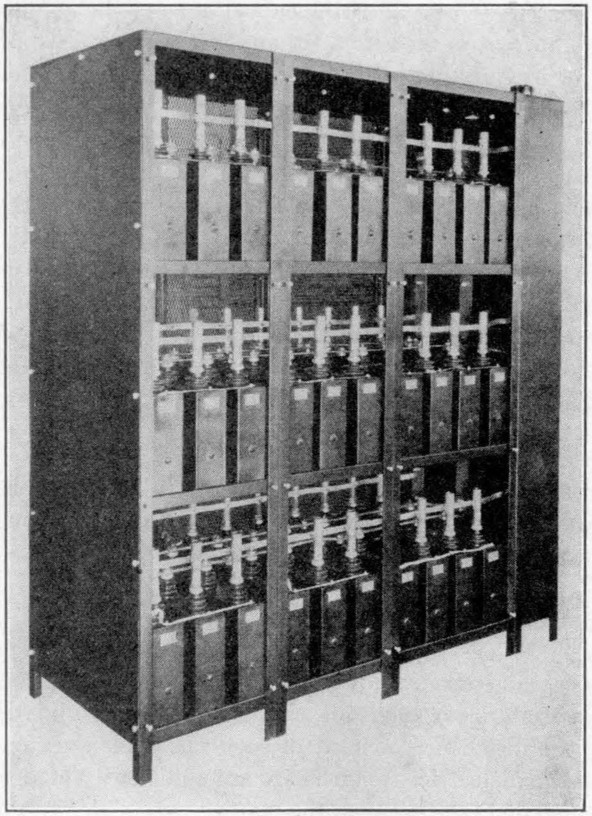
When several condensers are connected in series the reciprocal of the equivalent capacitance equals the sum of the reciprocals of the individual capacitances, or

94 $$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}.$$

The cost and space requirements for commercial condensers, called capacitors, is high for condensers using solid dielectrics because the dielectric constant of such materials does not exceed 13.3 and the dielectric strengths are not sufficiently high to permit a very small distance between the plates.

In the wet electrolytic capacitor an aluminum can contains various arrangements of aluminum foil with a large surface area and separated from the can by a cylindrical sheet of perforated hard rubber. The can is then filled with an electrolyte such as an aqueous solution of boric acid and ammonium or sodium borate. Other electrolytes are employed when a lower freezing point is required.

In the dry electrolytic capacitor two strips of aluminum foil are wound with two impregnated strips of separating paper to form a cylinder. The paper strips are impregnated with an electrolyte like that used in the wet type. In both types the anode must be



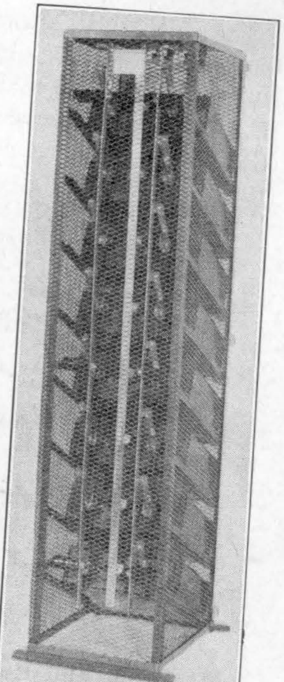
Westinghouse Electric and Manufacturing Co.

Capacitor, rated at 900 kva, 2400 volts at 60 cps.

treated electrolytically to form a surface layer of aluminum oxide (Al_2O_3) about 10^{-5} centimeter thick and possessing a high dielectric strength from the aluminum foil to the electrolyte but not in the other direction. The dielectric constant is about 10. Both anode and cathode may be treated in the dry electrolytic capacitor but

not in the wet electrolytic capacitor so that in the latter type two capacitors must be connected in series with opposing polarities on alternating-current circuits. Both types are adapted only for intermittent service.

In the " Pyranol " capacitor two strips of aluminum foil separated by two strips of impregnated paper are wound spirally to form a cylinder. In this type no electrolytic preparation of the anode strip is required and service may be continuous. The impregnating material (" Pyranol ") is a synthetic non-inflammable and non-explosive liquid possessing a very high dielectric strength similar to that of dry mineral oil. The dielectric constant is 4.5. This capacitor may be used singly in alternating- as well as direct-current circuits. It will be seen that the gain in capacitance in both the electrolytic and " Pyranol " capacitors is obtained by closer spacing of the plates rather than by an increase in the dielectric constant of the separating material.



General Electric Co.

Capacitor, rated at 120 kva, 460 volts at 60 cps.

Current Established in Capacitance by a Sinusoidal Emf. When a sinusoidal emf, $e = E_m \sin \omega t$, is impressed upon a condenser of C farads capacitance (Fig. 110) the current, from 92, is given by

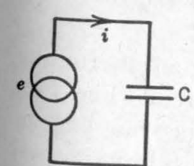


FIG. 110

$$i = C\frac{d(E_m \sin t\omega)}{dt} = C\omega E_m \cos \omega t$$

$$= C\omega E_m \sin (\omega t + 90°)$$

or

95 $$i = \frac{E_m}{\dfrac{1}{C\omega}} \sin (\omega t + 90°) \text{ amperes.}$$

The wave and vector diagrams for such a circuit are given in Fig. 111. It will be observed that the current leads the emf by 90 degrees and the maximum current equals the maximum emf (E_m) divided by the reciprocal of the product of the capacitance (C) and the angular velocity (ω).

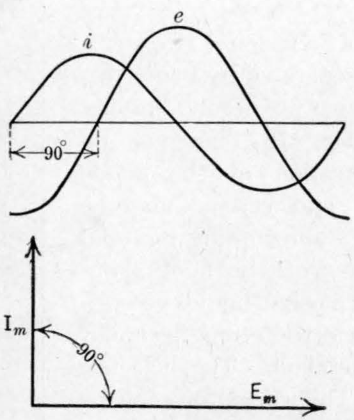


FIG. 111

Maximum Emf Required to Maintain a Sinusoidal Current in Resistance, Inductance, and Capacitance, respectively. The maximum value (E_m) of the sinusoidal emf required to maintain a sinusoidal current of maximum value (I_m) in resistance, inductance, and capacitance respectively may be summarized as follows:

Resistance (R)	$E_m = I_m R$	e and i in phase.
Inductance (L)	$E_m = I_m L\omega$	e leads i by 90 degrees.
Capacitance (C)	$E_m = \dfrac{I_m}{C\omega}$	e lags i by 90 degrees.

The Series Alternating-current Circuit. When an alternating current, $i = I_m \sin \omega t$, is established in a series circuit (Fig. 112) containing resistance, inductance, and capacitance an emf of maximum value ($I_m R$) in phase with the current must be impressed upon the resistance, an emf of maximum value ($I_m L\omega$) leading the current by 90 degrees must be impressed upon the inductance, and an emf of maximum value $\left(\dfrac{I_m}{C\omega}\right)$ lagging the current by 90 degrees must be impressed upon the capacitance. The maximum

value (E_m) of the emf that must be impressed upon the entire circuit, from Fig. 113, is given by $E_m = \sqrt{(I_m R)^2 + \left(I_m L\omega - \dfrac{I_m}{C\omega}\right)^2}$ or

96 $$E_m = I_m \sqrt{R^2 + \left(L\omega - \frac{1}{C\omega}\right)^2} \text{ volts.}$$

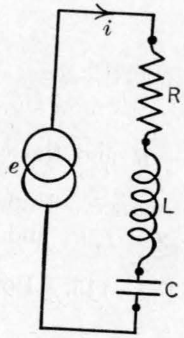


FIG. 112

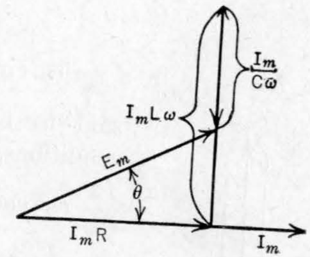


FIG. 113

Computations involving series connections are simplified by replacing $L\omega$, $\dfrac{1}{C\omega}$, $L\omega - \dfrac{1}{C\omega}$ and $\sqrt{R^2 + \left(L\omega - \dfrac{1}{C\omega}\right)^2}$ by the following symbols:

SYMBOL	DESIGNATION	UNIT
$X_L = L\omega$	inductive reactance	ohm
$X_C = \dfrac{1}{C\omega}$	capacitive reactance	ohm
$X = L\omega - \dfrac{1}{C\omega}$	reactance	ohm
$Z = \sqrt{R^2 + \left(L\omega - \dfrac{1}{C\omega}\right)^2}$	impedance	ohm

In Fig. 114, the tangent of the phase angle (θ) by which the emf leads the current equals $\dfrac{I_m X}{I_m R}$ or

97 $$\theta = \tan^{-1} \frac{X}{R} \text{ degrees.}$$

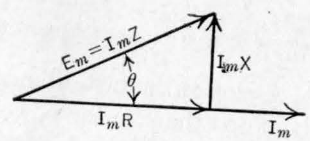


FIG. 114

The equation of the emf required to maintain a sinusoidal current, $i = I_m \sin \omega t$, in a series circuit is then given by

98 $$e = I_m Z \sin \left(\omega t + \tan^{-1} \frac{X}{R}\right) \text{ volts.}$$

When an emf, $e = E_m \sin \omega t$, is impressed upon a series circuit the current is given conversely by

99 $$i = \frac{E_m}{Z} \sin \left(\omega t - \tan^{-1} \frac{X}{R}\right) \text{ amperes.}$$

When $L\omega = \frac{1}{C\omega}$ in a series circuit, $Z = R$ and the circuit is said to be in resonance. Under these conditions, $E_m = I_m Z = I_m R$, and $I_m L\omega = \frac{I_m}{C\omega}$ as shown in Fig. 115. Both $I_m L\omega$ and $\frac{I_m}{C\omega}$ may be many times larger than the impressed emf, $I_m Z$. The impedance of any series connection may be reduced in this manner to a value equal to its resistance alone. This principle is employed in tuning radio receiving circuits for a definite frequency, $f = \frac{1}{2\pi\sqrt{LC}}$ cps, and for the similar adjustment of oscillating circuits as described in Chapter XIII.

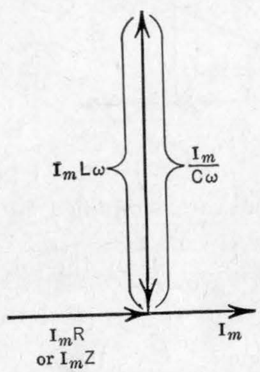


FIG. 115

Power Delivered by a Source of Sinusoidal Emf. If the current $i = I_m \sin (\omega t - \theta)$ is established in a circuit by a sinusoidal emf, $e = E_m \sin \omega t$, the power delivered to the circuit at any instant, from 3, is given by $p = (E_m \sin \omega t)\,(I_m \sin (\omega t - \theta)) = \frac{E_m I_m}{2} [\cos \theta - \cos (2\,\omega t - \theta)]$ watts.

A plot of the instantaneous power is shown in Fig. 116. It will be noted that (1) the power wave is sinusoidal in form, (2) the frequency of the power wave is twice that of the emf or current, (3) the axis of the power wave (shown in dot and dash) will coincide

with the axis of the emf and current waves only when $\theta = \pm 90$ degrees, and (4) the power during the interval (ab) and (cd) is negative; that is, the circuit during these intervals delivers power to the source of emf. The net energy delivered to the circuit during one cycle of the emf equals the sum of the areas under the power wave during the intervals (bc) and (da') minus the sum of the areas under the power wave during the intervals (ab) and (cd). The average power (P), or the net energy delivered to the circuit during one cycle divided by the period (T), is then given by $P = \frac{1}{T}\int_0^T \frac{E_m I_m}{2} [\cos \theta - \cos (2\,\omega t - \theta)]\, dt$

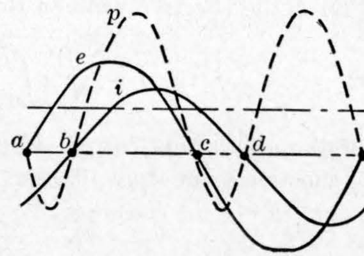


FIG. 116

or

100 $$P = \frac{E_m I_m \cos \theta}{2} \text{ watts.}$$

In any part of a circuit containing resistance (R) only, since $E_m = I_m R$ and θ equals zero, the average power absorbed by the resistance is given by

101 $$P = \frac{I_m{}^2 R}{2} \text{ watts.}$$

Effective Value of an Alternating Current or Emf. For practical purposes the magnitude of any wave form of alternating current such as that shown in Fig. 100 is designated by the magnitude of the direct current that will convert the same amount of electric energy into heat in the same time. The alternating current shown in Fig. 100 when flowing in a resistance (R) will convert electric energy into heat at any instant at a rate $i^2 R$ where $i = f(t)$; that is, some function of t or the equation of the alternating current. The total energy converted into heat in one cycle will be $\int_0^T i^2 R\, dt$.

The total energy converted into heat by a direct current (I_{dc}) flowing in the same resistance during the same time will be

I_{dc}^2RT. Equating the two, $I_{dc}^2RT = \int_0^T i^2R\,dt$ and, replacing I_{dc} by I, the effective value of the alternating current is given by

102 $$I = \sqrt{\frac{1}{T}\int_0^T i^2\,dt} \text{ amperes.}$$

If the alternating current is sinusoidal, that is, $i = I_m \sin \omega t$, the effective value from 102 is

103 $$I = \frac{I_m}{\sqrt{2}} \text{ amperes.}$$

Similarly for the emf

104 $$E = \frac{E_m}{\sqrt{2}} \text{ volts.}$$

It should be noted that the divisor ($\sqrt{2}$) applies to sine waves only but that the effective value of any wave form may be obtained from 102.

Power, Power Factor, and Kilovolt-amperes. The power formula (100) for sinusoidal emf and current may be rewritten, $P = \frac{E_m}{\sqrt{2}}\frac{I_m}{\sqrt{2}}\cos\theta$, and, since $\frac{E_m}{\sqrt{2}} = E$ and $\frac{I_m}{\sqrt{2}} = I$, the power in terms of the effective values of emf and current is given by

105 $$P = EI\cos\theta \text{ watts.}$$

The ratio of the power delivered to a circuit to the product of the effective emf and current, impressed upon and established in the circuit respectively, is called the power factor (pf) of the circuit. The power factor of any circuit is then given by

106 $$\text{pf} = \frac{P}{EI}$$

and, for a sinusoidal emf and current, by

107 $$\text{pf} = \cos\theta.$$

If each vector in Fig. 114 is divided by $\sqrt{2}$ the vectors will represent the effective values of the stated quantities as shown in Fig. 117. It will be noted that when all the electric energy delivered

to a circuit is converted into thermal energy as in Fig. 112 the power factor of the circuit is given by $\cos\theta = \frac{IR}{IZ}$ or

108 $$\text{pf} = \frac{R}{Z}.$$

The component (I') of the current (I) in Fig. 117 in phase with E is called the energy component of the current and the component (I'') differing in phase with E by 90 degrees is called the wattless component of the current.

The power converted in an alternating-current circuit is given by one of the three expressions:

109 $$P = \frac{EI\cos\theta}{1000} \text{ kilowatts,}$$

110 $$P = \frac{VI\cos\theta}{1000} \text{ kilowatts,}$$

111 $$P = \frac{I^2R}{1000} \text{ kilowatts.}$$

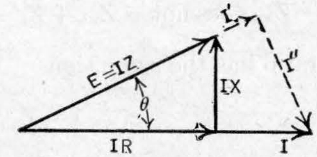


Fig. 117

The application of each formula is the same as that described under 3, 7, and 4.

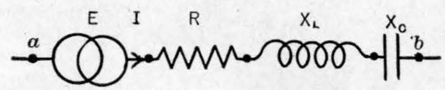


Fig. 118

The effective potential or voltage (V_{ab}) between two points (a and b in Fig. 118 for example) is given by

112 $$V_{ab} = E - IR - IX_L - IX_C \text{ volts,}$$

where E and I are the effective values of the emf and current and the subtraction is vectorial.

The kilovolt-amperes (KVA) delivered to any circuit is given by

113 $$KVA = \frac{VI}{1000} \text{ kilovolt-amperes.}$$

A Summary of the Alternating-current Series Circuit Relations. The following relations apply to Fig. 119:

$$R_{ad} = R_1 + R_2 \quad X_{ad} = X_1 - X_2 + X_3 - X_4,$$

$$Z_{ab} = \sqrt{R_1^2 + X_1^2} \quad Z_{bc} = \sqrt{R_2^2 + X_2^2} \quad Z_{cd} = X_3 - X_4.$$

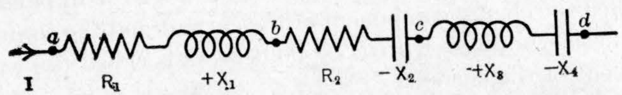


FIG. 119

Z_{ad} does not $= Z_{ab} + Z_{bc} + Z_{cd}$ unless $\dfrac{X_{ab}}{R_{ab}} = \dfrac{X_{bc}}{R_{bc}} = \dfrac{X_{cd}}{R_{cd}}$ and each ratio has the same sign.

$$Z_{ad} = \sqrt{R_{ad}^2 + X_{ad}^2},$$

$$V_{ab} = IZ_{ab} \qquad V_{bc} = IZ_{bc} \qquad V_{cd} = IZ_{cd}.$$

V_{ad} does not $= V_{ab} + V_{bc} + V_{cd}$ unless $\dfrac{X_{ab}}{R_{ab}} = \dfrac{X_{bc}}{R_{bc}} = \dfrac{X_{cd}}{R_{cd}}$ and each ratio has the same sign.

$$V_{ad} = IZ_{ad}.$$

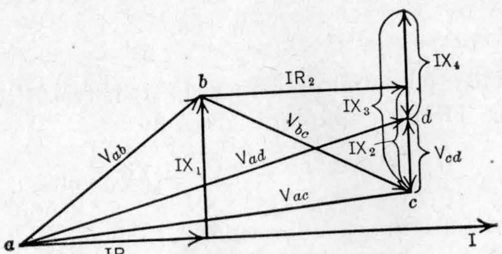


FIG. 120

The complete vector diagram for Fig. 119 is shown in Fig. 120, all vectors being located in accordance with the principles stated on page 106 and measured by effective values.

$$\cos\theta_{ab} = \frac{R_{ab}}{Z_{ab}}, \quad \cos\theta_{bc} = \frac{R_{bc}}{Z_{bc}}, \quad \cos\theta_{cd} = \frac{R_{cd}}{Z_{cd}}, \quad \cos\theta_{ad} = \frac{R_{ad}}{Z_{ad}}.$$

$$P_{ab} = V_{ab}I\cos\theta_{ab} = I^2R_{ab}, \qquad P_{bc} = V_{bc}I\cos\theta_{bc} = I^2R_{bc},$$

$$P_{cd} = V_{cd}I\cos\theta_{cd} = I^2R_{cd}, \qquad P_{ad} = V_{ad}I\cos\theta_{ad} = I^2R_{ad},$$

$$P_{ad} = P_{ab} + P_{bc} + P_{cd}.$$

The Parallel Connection in an Alternating-current Circuit. The vector diagram of a typical parallel connection (Fig. 121) is

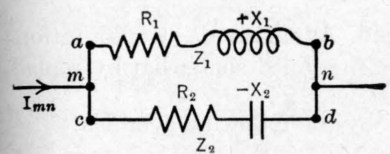


FIG. 121

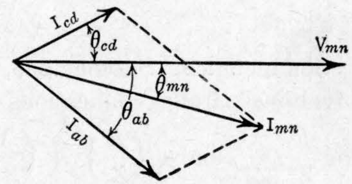


FIG. 122

shown in Fig. 122, all vectors being referred to the effective potential (V_{mn}) between m and n. In Fig. 121, $I_{ab} = \dfrac{V_{mn}}{Z_1}$, $I_{cd} = \dfrac{V_{mn}}{Z_2}$, $\cos\theta_{ab} = \dfrac{R_1}{Z_1}$ and $\cos\theta_{cd} = \dfrac{R_2}{Z_2}$. I_{mn} equals the vector sum of I_{ab} and I_{cd} as shown in Fig. 122. The magnitude and phase relation of I_{mn} may be determined from its horizontal and vertical components as explained in the addition of emf's on page 100. The horizontal component of I_{mn} is given by

$$\Sigma H = \frac{V_{mn}}{Z_1}\cdot\frac{R_1}{Z_1} + \frac{V_{mn}}{Z_2}\cdot\frac{R_2}{Z_2} = V_{mn}\left(\frac{R_1}{Z_1^2} + \frac{R_2}{Z_2^2}\right).$$

The vertical component of I_{mn} is given by

$$\Sigma V = -\frac{V_{mn}}{Z_1}\cdot\frac{X_1}{Z_1} + \frac{V_{mn}}{Z_2}\cdot\frac{X_2}{Z_2} = -V_{mn}\left(\frac{X_1}{Z_1^2} - \frac{X_2}{Z_2^2}\right).$$

Since $I_{mn} = \sqrt{(\Sigma H)^2 + (\Sigma V)^2}$,

$$I_{mn} = \sqrt{\left[V_{mn}\left(\frac{R_1}{Z_1^2} + \frac{R_2}{Z_2^2}\right)\right]^2 + \left[-V_{mn}\left(\frac{X_1}{Z_1^2} - \frac{X_2}{Z_2^2}\right)\right]^2} \text{ or}$$

114 $$I_{mn} = V_{mn}\sqrt{\left(\frac{R_1}{Z_1^2} + \frac{R_2}{Z_2^2}\right)^2 + \left(\frac{X_1}{Z_1^2} - \frac{X_2}{Z_2^2}\right)^2} \text{ amperes.}$$

The phase angle (θ_{mn}) equals $\tan^{-1}\dfrac{\Sigma V}{\Sigma H}$ or

115 $$\theta_{mn} = \tan^{-1} - \left(\frac{\dfrac{X_1}{Z_1^2} - \dfrac{X_2}{Z_2^2}}{\dfrac{R_1}{Z_1^2} + \dfrac{R_2}{Z_2^2}}\right) \text{ degrees.}$$

Conductance, Susceptance, and Admittance. Computations involving parallel connections are simplified somewhat by replacing $\dfrac{R}{Z^2}$, $\dfrac{X}{Z^2}$, and $\sqrt{\left(\dfrac{R}{Z^2}\right)^2 + \left(\dfrac{X}{Z^2}\right)^2}$ by the following symbols:

Symbol	Designation	Unit
$G = \dfrac{R}{Z^2}$	conductance	mho
$B = \dfrac{X}{Z^2}$	susceptance	mho
$Y = \sqrt{\left(\dfrac{R}{Z^2}\right)^2 + \left(\dfrac{X}{Z^2}\right)^2}$	admittance	mho

Formula 114 may then be written,

$$I_{mn} = V_{mn}\sqrt{(G_1 + G_2)^2 + (B_1 + B_2)^2} = V_{mn}\sqrt{(G_{mn})^2 + (B_{mn})^2} \text{ or}$$

116 $$I_{mn} = V_{mn}\, Y_{mn} \text{ amperes.}$$

The phase angle (θ_{mn}) by which I_{mn} lags V_{mn} is given by

117 $$\theta_{mn} = \tan^{-1}\left(\frac{B_{mn}}{G_{mn}}\right) \text{ degrees.}$$

The vector diagram for any part of an alternating-current circuit expressed in terms of conductance, susceptance, and admittance is shown in Fig. 123 (the admittance diagram) and the vector

diagram for the same part of the circuit expressed in terms of resistance, reactance, and impedance is shown in Fig. 124 (the impedance diagram). Since $I = VY = \dfrac{V}{Z}$, it follows that

118 $$Y = \frac{1}{Z} \text{ mhos or } Z = \frac{1}{Y} \text{ ohms.}$$

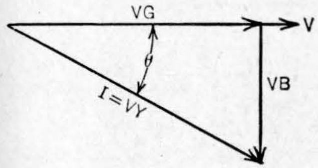


FIG. 123

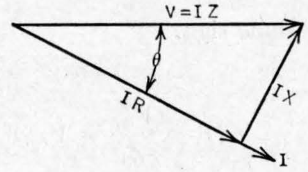


FIG. 124

In Fig. 123, $\cos\theta = \dfrac{G}{Y}$ and in Fig. 124, $\cos\theta = \dfrac{R}{Z}\cdot$ Then $\dfrac{R}{Z} = \dfrac{G}{Y}$ and since $\dfrac{R}{Z} = RY$,

119 $$R = \frac{G}{Y^2} \text{ ohms.}$$

In Fig. 123, $\sin\theta = \dfrac{B}{Y}$ and in Fig. 124, $\sin\theta = \dfrac{X}{Z}\cdot$ Then $\dfrac{X}{Z} = \dfrac{B}{Y}$ and since $\dfrac{X}{Z} = XY$,

120 $$X = \frac{B}{Y^2} \text{ ohms.}$$

When the resultant susceptance (B) of a parallel connection equals zero, $Y = G$ and the parallel connection is said to be in resonance.

A Summary of the Alternating-current Parallel Connection Relations. The following relations apply to Fig. 121:

$$G_{ab} = \frac{R_1}{Z_1^2} \qquad G_{cd} = \frac{R_2}{Z_2^2} \qquad G_{mn} = G_{ab} + G_{cd}$$

$$B_{ab} = \frac{X_1}{Z_1^2} \qquad B_{cd} = \frac{-X_2}{Z_2^2} \qquad B_{mn} = B_{ab} + B_{cd}.$$

It should be noted that the summation of conductances is arithmetic while the summation of susceptances is algebraic since the reactance is positive for inductive reactance and negative for capacitive reactance.

$$Y_{ab} = \sqrt{G_{ab}^2 + B_{ab}^2} \qquad Y_{cd} = \sqrt{G_{cd}^2 + B_{cd}^2}.$$

Y_{mn} does not $= Y_{ab} + Y_{cd}$ unless $\dfrac{B_{ab}}{G_{ab}} = \dfrac{B_{cd}}{G_{cd}}$ and each ratio has the same sign.

$$Y_{mn} = \sqrt{(G_{mn})^2 + (B_{mn})^2}.$$

$$I_{ab} = \frac{V_{mn}}{Z_1} = V_{mn}Y_{ab} \qquad I_{cd} = \frac{V_{mn}}{Z_2} = V_{mn}Y_{cd}.$$

I_{mn} does not $= I_{ab} + I_{cd}$ unless $\dfrac{B_{ab}}{G_{ab}} = \dfrac{B_{cd}}{G_{cd}}$ and each ratio has the same sign.

$$I_{mn} = \frac{V_{mn}}{Z_{mn}} = V_{mn}Y_{mn},$$

$$\cos\theta_{ab} = \frac{R_1}{Z_1} = \frac{G_{ab}}{Y_{ab}} \qquad \cos\theta_{cd} = \frac{R_2}{Z_2} = \frac{G_{cd}}{Y_{cd}},$$

$$\cos\theta_{mn} = \frac{R_{mn}}{Z_{mn}} = \frac{G_{mn}}{Y_{mn}},$$

$$R_{mn} = \frac{G_{mn}}{Y_{mn}^2} \qquad X_{mn} = \frac{B_{mn}}{Y_{mn}^2}.$$

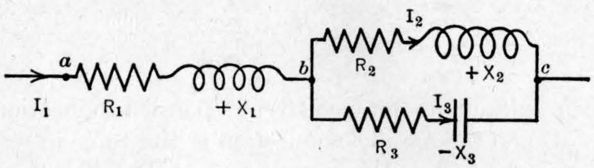


FIG. 125

The Series-parallel Alternating-current Circuit. When an alternating-current circuit contains parallel connections the equivalent resistance and reactance of each parallel connection must be determined and the equivalent series connection substituted

for each parallel connection. In Fig. 125, for example, $G_{bc} = G_2 + G_3$ and $B_{bc} = B_2 + B_3$. Then $R_{bc} = \dfrac{G_{bc}}{G_{bc}^2 + B_{bc}^2}$ and $X_{bc} = \dfrac{B_{bc}}{G_{bc}^2 + B_{bc}^2}$.

$R_{ac} = R_1 + R_{bc}$, $X_{ac} = X_1 + X_{bc}$, and $Z_{ac} = \sqrt{R_{ac}^2 + X_{ac}^2}$.

$I_1 = I_{ac} = I_{bc} = \dfrac{V_{ac}}{Z_{ac}}$. $Z_{bc} = \sqrt{R_{bc}^2 + X_{bc}^2}$ and $V_{bc} = I_{bc}Z_{bc}$.

Then $I_2 = \dfrac{V_{bc}}{Z_2}$ and $I_3 = \dfrac{V_{bc}}{Z_3}$.

Practice problems with answers for Chapter VI will be found on pages 258 to 265.

CHAPTER VII

ALTERNATING-CURRENT MEASUREMENTS

Measurement of Effective Current and Potential. In any instrument which indicates the effective value of an alternating current the force acting on the moving element at any instant, from 102, must be proportional to i^2, the square of the instantaneous current, and the moving element must take a position corresponding to the average value of the squared instantaneous currents during one cycle; that is, the deflection must be proportional to $\frac{1}{T}\int_0^T i^2\,dt$. The deflection being proportional to the average square of the currents, the scale divisions on such instruments will not be as uniform as on the direct-current instrument described on page 85.

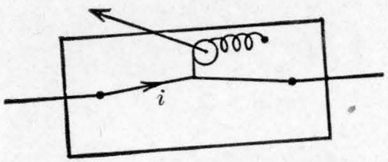


FIG. 126

The Hot-wire Ammeter. A platinum-silver wire is stretched between two insulated points on a bronze plate of the same coefficient of expansion, as shown in Fig. 126. Since the heating effect of an electric current (i) is proportional to i^2R the temperature of the platinum-silver wire when conducting an alternating current will be a function of $\frac{1}{T}\int_0^T i^2\,dt$, the mass of the wire being sufficient to maintain it at a constant temperature while the current passes through its cyclical values. The length of the wire, being a function of its temperature, is then dependent upon $\frac{1}{T}\int_0^T i^2\,dt$.

A string attached to the center of the wire is wound around a small pulley and is held taut by a spring so that any change in the length of the wire is indicated by the proportional angular motion of a pointer attached to the pulley.

This instrument, called a hot-wire ammeter, will then indicate the effective value of an alternating current. The instrument is seldom used for ordinary measurements of current since it must be calibrated frequently and is somewhat sluggish in action. It is sometimes employed in circuits in which the effective value of the current varies rapidly (making use of its sluggish characteristic) and is applied extensively to the measurement of alternating currents of high frequency (as in radio telegraph and telephone circuits). It is used frequently as a comparison instrument in the calibration of alternating-current instruments, the deflection of the hot-wire ammeter due to an unknown alternating current being later interpreted by a known direct current producing the same deflection. A hot-wire voltmeter may be constructed on the same principle (a high resistance is connected in series with the platinum-silver wire) but the instrument possesses no particular advantages.

The Thermocouple Ammeter and Voltmeter. If two different metals or alloys, such as chromium-nickel and copper-nickel, are butt-welded and attached at their junctions to a wire heated by the current to be measured, as shown in Fig. 127, a direct emf will be generated at the junction which is proportional to the effective value of the current in the wire. A direct-current millivoltmeter connected to the terminals of the thermocouple will indicate the effective value of a current of any wave form or frequency. The thermocouple and heater are usually enclosed in an evacuated glass bulb to provide radiation of heat from the couple and to reduce the effect of external temperature variations. The instrument is especially adapted to the measurement of very small currents since it responds to a current of a few microamperes in magnitude. The thermocouple voltmeter has a high resistance connected in series with the heated wire and operates in the same manner as the ammeter.

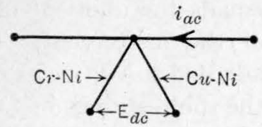


FIG. 127

The Electrodynamometer Ammeter and Voltmeter. A pivoted movable coil controlled by spiral springs is placed within a fixed

coil as shown in Fig. 128. The flux density (B) due to the fixed coil, from 37, is proportional to the current (i) and since the movable coil is connected in series with the fixed coil and carries the same current (i) the force acting on the movable coil, from 36, is proportional to iB or i^2. The movable coil then takes up a position proportional to $\frac{1}{T}\int_0^T i^2\,dt$ by reason of its inertia. The instrument constructed as shown in Fig. 128 and called an electrodynamometer ammeter is adapted to the direct measurement of an alternating current not exceeding 0.75 ampere in effective value, the current being limited by the current capacity of the spiral springs through which electrical connections are made to the moving coil. Electrodynamometer ammeters designed to measure currents up to 10 amperes are sometimes made (the movable coil is then shunted) but such instruments require careful adjustment for accurate measurement at all frequencies and are not generally used.

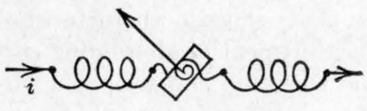


FIG. 128

In the electrodynamometer voltmeter a high non-inductive resistance is connected in series with the unit shown in Fig. 128, the resistances of the fixed and movable coils also being higher than in the electrodynamometer ammeter. The deflection of the voltmeter is then a function of the effective potential between its terminals since the effective current which produces the deflection equals the quotient of the effective potential and the resistance of the instrument. The electrodynamometer principle is well adapted to voltmeter construction since the current conducted by the spiral springs in a voltmeter does not exceed a few hundredths of an ampere except in the low-range instruments (0.5 ampere in a one-volt voltmeter). Most alternating-current voltmeters are therefore of the electrodynamometer type.

The Iron Vane Ammeter and Voltmeter. If an iron vane is placed within an inclined coil conducting an alternating current as shown in Fig. 129, the force acting on the iron vane at any instant is proportional to the square of the flux density due to the current in the coil (see page 33). Since the flux density due to the current is proportional to the current the force acting on the iron

vane is proportional to the square of the current. The pointer attached to the iron vane will then take up a position proportional to $\frac{1}{T}\int_0^T i^2\,dt$ by reason of the inertia of the moving element. A spiral spring attached to the moving element provides the reactive torque as in instruments previously described. The iron vane principle is well adapted to ammeter construction since the moving element carries no current. Most alternating-current ammeters are therefore of the iron vane type.

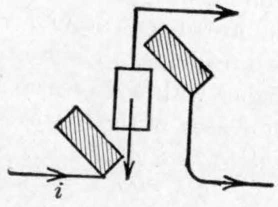
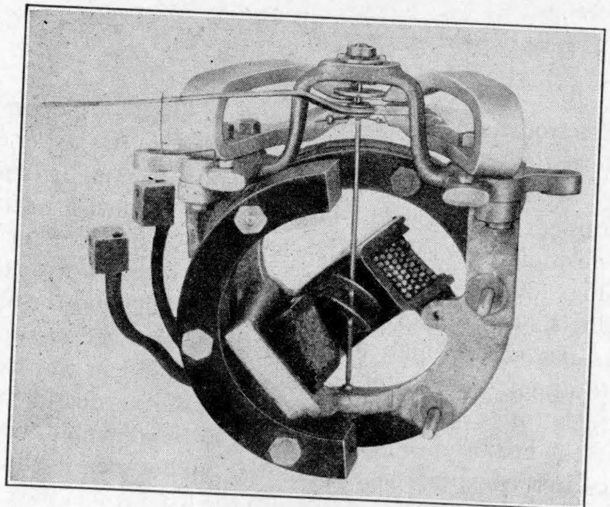


FIG. 129

In the iron vane voltmeter a high non-inductive resistance is connected in series with the inclined coil which is also of higher resistance than the coil used in the iron vane ammeter. The deflection of the pointer, as in the electrodynamometer voltmeter, is then a function of the effective potential between the terminals of the instrument. The iron vane voltmeter is seldom used for accurate measurements, however, because of the superior qualities of the electrodynamometer type.


General Electric Co.
Construction of Iron-vane Ammeter.

As previously noted in Chapter V, the electrodynamometer and the iron vane instruments may be employed for the measurement of direct current or potential but are subject to a small error due to terrestrial magnetism. If terrestrial magnetism aids that due to the fixed coil, the reading will be too high and, if it opposes, the reading will be too low. This error may be rectified by turning the instrument around 180 degrees and taking the average of the two readings. The iron vane type in direct-current circuits reads higher with a decreasing current than with an increasing current by reason of the hysteresis effect.

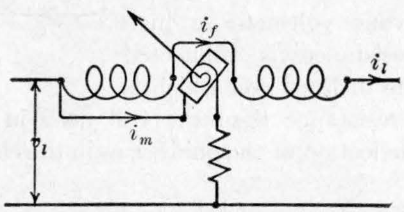
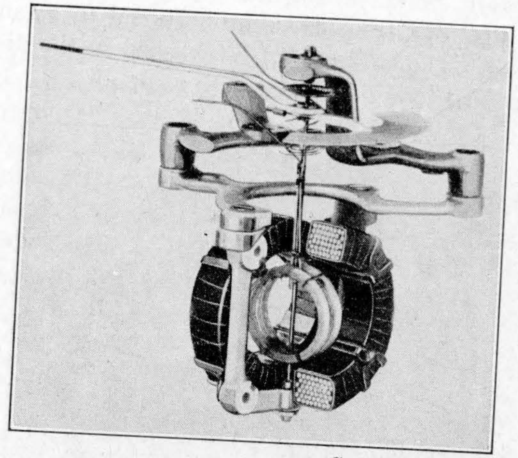


FIG. 130

The Electrodynamometer Wattmeter. Since the power factor of an alternating-current circuit is seldom known the power cannot generally be determined from voltmeter and ammeter readings. An instrument measuring the power directly, called a wattmeter, is therefore indispensable. In the electrodynamometer wattmeter (Fig. 130) the fixed coil is connected in series with the line (or conducts a certain portion of the line current) and the movable coil in series with a high non-inductive resistance is connected across the line. The instantaneous current (i_f) in the fixed coil then equals (or is proportional to) the instantaneous line current (i_l), and the instantaneous current (i_m) in the movable coil is proportional to the instantaneous potential (v_l) between the line wires. The instantaneous flux density due to the fixed coil is then proportional to i_l and, from 36, the force acting upon the movable coil is proportional to $v_l i_l$ or the instantaneous power supplied through the line to which the wattmeter is connected. The deflection of a pointer attached to the movable coil by reason of its inertia will then be proportional to the average power in any case, or $V_l I_l \cos\theta$ when both V_l and I_l are sinusoidal. When applied to a direct-

current circuit the average of two readings must be obtained by turning the instrument through 180 degrees or by reversing both potential and current coils.



General Electric Co.

Construction of Electrodynamometer Wattmeter.

The Induction Watthour Meter. While the Thomson watthour meter described on page 89 may be employed with slight alteration for the measurement of energy in an alternating-current

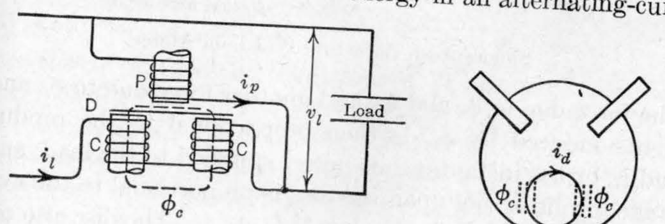
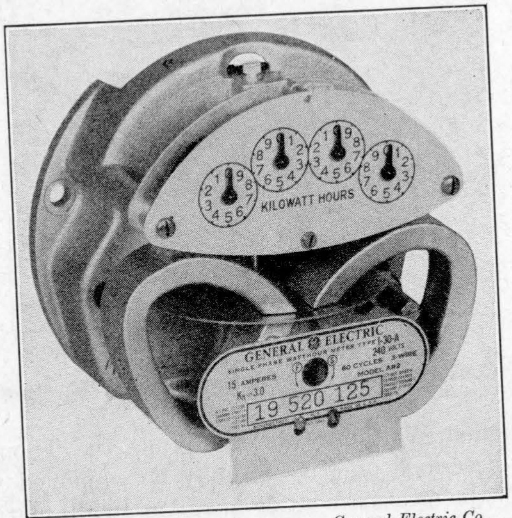


FIG. 131

circuit the induction watthour meter shown in Fig. 131 is better adapted for the purpose. A revolving disc (D) is mounted between a potential coil (P) and the current coils (CC). The flux (ϕ_c) permeating the disc due to the current coils is proportional to and in phase with i_l. The instantaneous current (i_p) flowing in the potential coil (P) is proportional to the instantaneous line potential

(v_l) but lags it by nearly 90 degrees by reason of the highly inductive character of the potential coil. The flux (ϕ_p) due to the potential coil current is proportional to and in phase with the potential coil current (i_p). The emf (e_d) generated in the disc (D) by the alternating flux (ϕ_p), from 53, is proportional to ϕ_p and leads it by 90 degrees. The current (i_d) established in the disc by e_d is then proportional to and in phase with v_l.

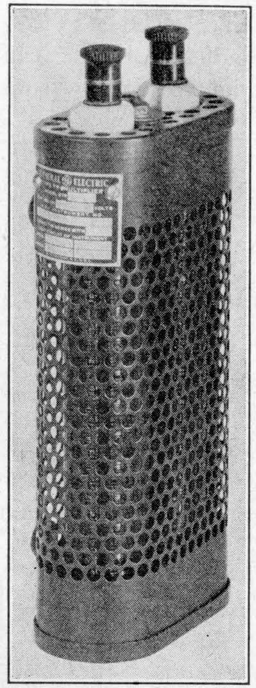


General Electric Co.

Single-phase Induction Watthour Meter.

The force due to ϕ_c and i_d, and another force due to ϕ_p and the currents induced by ϕ_c, is then proportional to the product of v_l and i_l, or the instantaneous power supplied to the load, and the average torque acting upon the disc is proportional to the average power (P) supplied to the load or $V_l I_l \cos \theta$. The disc also rotates between the poles of two or more permanent magnets and the reactive torque (as described on page 90) acting on the disc is therefore proportional to the speed (S) of the disc. Then $P = KS$ and the energy (W) supplied to the load in any time (t) is given by $W = Pt = KSt$ or $W = KR$ where R is the number of revolutions of the disc in the time (t). A series of dials (similar to those shown in Fig. 91) geared to the disc shaft will then indicate the number of kilowatthours supplied to the load in a given time.

Instrument Transformers. The potential coils of most alternating-current instruments are designed for direct connection to circuits of 150 volts effective potential between line wires (300, 600, and 750 volt instruments are also available) and the current coils are usually designed to conduct not more than 5 amperes effective current. High non-inductive resistances, called extension coils or multipliers, may be connected in series with potential coils when the effective line potential exceeds the range of the instrument. The potential reading of the instrument is then multiplied by the ratio $\left(\dfrac{R_p + R_m}{R_p}\right)$ where R_p is the resistance of the potential coil and R_m is the resistance of the multiplier. This use of the multiplier to increase the range of an instrument is restricted, however, to instruments in which the inductance of the potential coil is negligible.



General Electric Co.

Potential Coil Multiplier for Direct-current and Alternating-current Instruments.

The shunting of current coils to increase the range of an instrument is not as desirable in alternating- as in direct-current instruments since the division of current in the alternating-current instrument between the current coil and the shunt will depend upon the frequency of the current unless the inductance of each connection is made negligible. The range of alternating-current instruments is extended most conveniently and accurately by connecting potential and current transformers to the potential and current coils as shown in Fig. 132. The line current (I_l) then equals $T_c I_c$ and the line potential (V_l) equals $T_p V_p$, where T_c and T_p are the ratios of transformation of the current and potential transformers respectively. The principle of the transformer is discussed on page 189.

The Frequency Meter. The measurement of frequency is often accomplished by an instrument in which a series of steel reeds

(Fig. 133) of definite successive frequencies of vibration are placed in the alternating magnetic field produced by a coil of high-resistance wire connected across the line. The frequency of the alternating magnetic flux will then be the same as that of the line potential and the reed of the same frequency will be set in vibration. The end of each reed is painted white and the frequency is indicated by the white blur produced opposite a scale indicating the frequency of each reed.

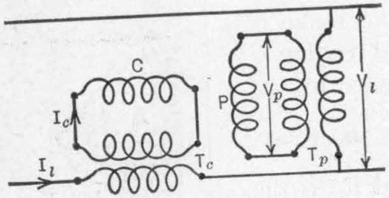


FIG. 132

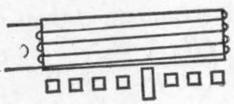


FIG. 133

In other frequency meters the frequency is indicated directly by a pointer on a scale. In the instrument shown in Fig. 134, for example, two fixed coils (*A* and *B*) located 90 degrees apart are connected to the terminals (*TT*) by resistances and reactances

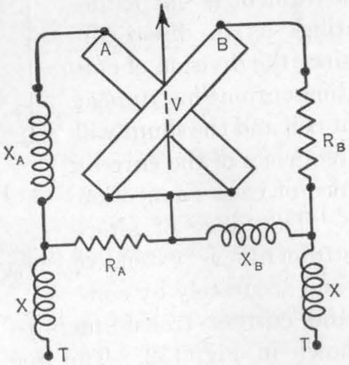
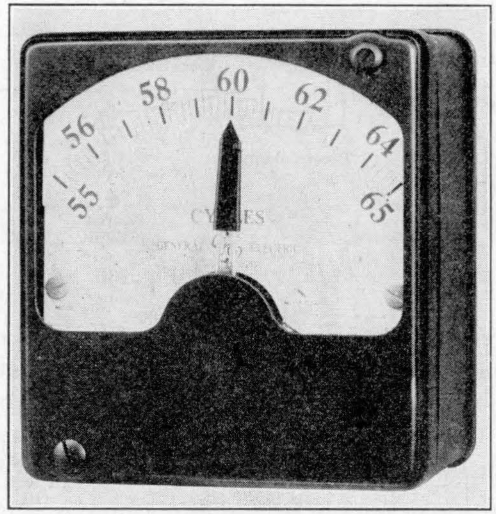


FIG. 134

as indicated. The pointer is attached to an iron vane (*V*) on a shaft which has no controlling spring. At some definite frequency the pointer will take a position determined by the relative forces on the iron vane due to the two coils. An increase in frequency will

reduce the current in coil *A*, increase the current in coil *B*, and change the position of the vane and the pointer. A decrease in frequency will cause the pointer to take a position in the other



General Electric Co.

Alternating-current Frequency Meter.

direction. The reactances (*XX*) suppress higher harmonics if the wave form is non-sinusoidal. Changes of potential between the terminals affect both coils equally and do not alter the position of the needle.

The Oscillograph. The wave form of an alternating current may be photographed with an instrument, called an oscillograph, which contains a vibrator, an intense concentrated source of light, and a photographic film attached to the surface of a rotating drum. The vibrator consists of a doubled fine strip of copper held taut between the poles of a powerful electromagnet as shown in Fig. 135. A small mirror cemented to the copper strip reflects a spot of light onto the film covering the rotating drum as shown in Fig. 136. When an alternating current is sent through the vibrator the angular twist of the vibrator at any instant is proportional to the instantaneous current.

A horizontal line of light would then be seen on the surface of the drum parallel to its axis, the length of the line (to scale) being equal to twice the maximum value of the vibrator current. Since the drum is rotated at constant speed the sensitized film on its

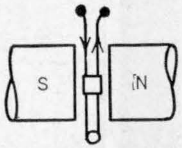


Fig. 135

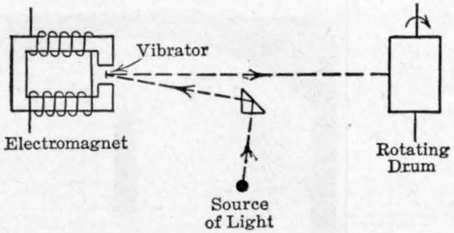
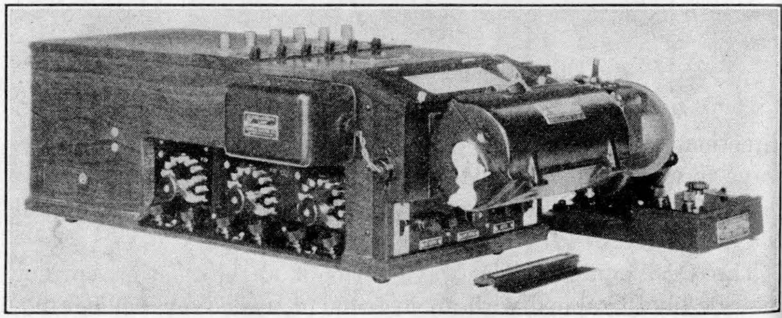


Fig. 136

surface will record the successive positions of the spot of light and when developed will reveal the wave form of the vibrator current. If light is reflected from two vibrators onto the drum, one vibrator being connected across the line in series with a non-inductive resistance and the other vibrator connected in series with the line



General Electric Co.

Vibrator-type Oscillograph.

(usually shunted by a low resistance), the simultaneous wave forms of the line potential and the line current including their phase relation may be photographed. If the surface of the rotating drum is covered with several plane mirrors the vibrating spots of light may again be reflected upward to a plate of ground glass. The wave forms may then be seen and traced upon thin paper.

In the cathode-ray oscillograph shown in Fig. 137 an evacuated glass tube contains an indirectly heated cathode (C), several accelerating and concentrating anodes (A_1, A_2, and A_3), two electrostatically deflecting plates (D_1 and D_2), and a fluorescent screen (F). Electrons drawn from the cathode by the anode (A_1) are concentrated and accelerated by the anodes (A_2 and A_3). The resultant cathode ray is deflected by the variable potential (under investigation) at (D_1), and then by the sawtooth potential

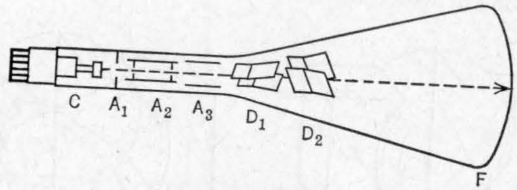


Fig. 137

wave of the time-deflecting plates at (D_2). The wave form of the potential at (D_1) is reproduced on the fluorescent screen at (F). The deflection may be produced electromagnetically by replacing the plates by two coils of wire located at right angles to each other. Since the cathode ray possesses negligible inertia this type of oscillograph will reproduce intricate wave forms and high frequency phenomena with great accuracy. The electronic theory involved in the cathode-ray oscillograph will be made clearer after reading Chapter XIII.

Practice problems with answers for Chapter VII will be found on pages 265 to 266.

CHAPTER VIII

THREE-PHASE ALTERNATING CURRENTS

The Generation of Three-phase Emf's. A single-phase generator has one armature winding (represented by the single turn xa in Fig. 138) in which an emf, $e_{xa} = E_m \sin \omega t$, is generated. A

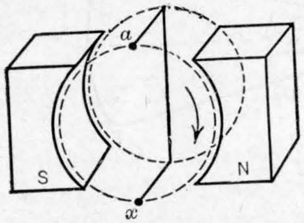


FIG. 138

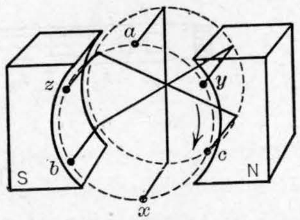


FIG. 139

three-phase generator has three armature windings (represented by the single turns xa, yb, and zc in Fig. 139) located 120 degrees apart and in which the respective generated emf's differ in phase by

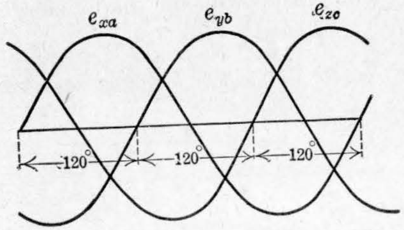


FIG. 140

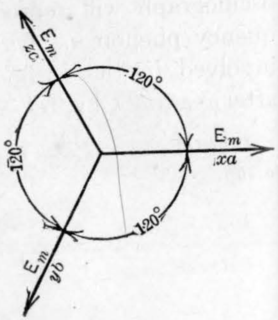


FIG. 141

120 degrees. The three generated emf's may be represented mathematically by $e_{xa} = E_m \sin \omega t$, $e_{yb} = E_m \sin (\omega t - 120°)$, and $e_{zc} = E_m \sin (\omega t - 240°)$. The same emf's may be represented by a wave diagram (Fig. 140) and by a vector diagram (Fig. 141).

The Three-phase Y Connection. If the three armature windings of a three-phase generator are connected independently by six slip rings to three identical loads, $x'a'$, $y'b'$, and $z'c'$ as shown in Fig. 142 the line currents i_{xa}, i_{yb}, and i_{zc} will also differ in phase by 120 degrees and each current will differ in phase with its emf by

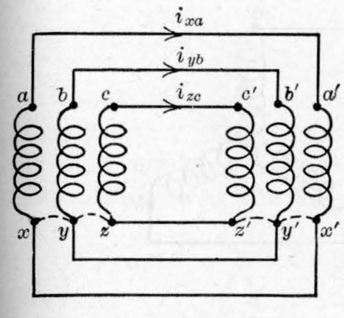


FIG. 142

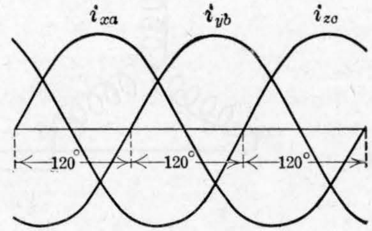


FIG. 143

the same angle (θ). The load is then said to be balanced and a balanced load is assumed throughout the chapter. The currents, referred to i_{xa}, may be represented mathematically by $i_{xa} = I_m \sin \omega t$, $i_{yb} = I_m \sin (\omega t - 120°)$, and $i_{zc} = I_m \sin (\omega t - 240°)$. The same currents may be represented by a wave diagram (Fig. 143) and by a vector diagram (Fig. 144).

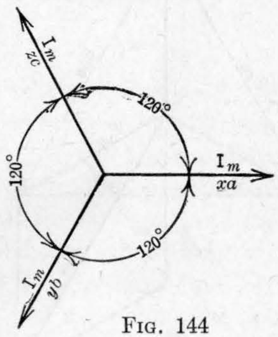


FIG. 144

It will be noted (Fig. 143 for example) that $i_{xa} + i_{yb} + i_{zc} = 0$; that is, in Fig. 142, the sum of the currents at any instant flowing to the right between xx', yy', and zz' equals the sum of the currents at the same instant flowing to the left. The line wires xx', yy', and zz' are therefore unnecessary. If these line wires are removed and the terminals xyz and $x'y'z'$ are connected as shown by the dotted lines the system may be operated with one-half the weight of line wire required in the previous arrangement. It will be shown later that, in comparison with a single-phase system, the saving in weight is not one-half but one-quarter.

The latter connection, called a Y connection, is usually represented by the connection diagram shown in Fig. 145, substituting *oa* for *xa*, *ob* for *yb*, *oc* for *zc*, etc. The connection point (*o*), common to all three windings, is called the neutral point of the generator; *o'* is the neutral point of the load. E_{oa}, E_{ob}, and E_{oc} are

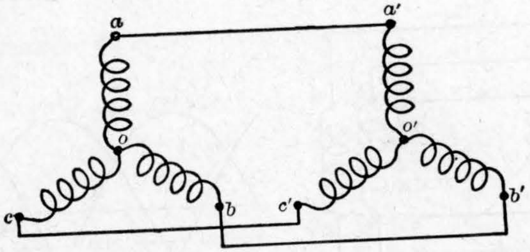


FIG. 145

called the effective phase emf's (E_p) and E_{ab}, E_{bc}, and E_{ca} are called the effective line emf's (E_l) of the generator. The vector diagram of the phase emf's and line emf's of a Y-connected three-phase generator is usually constructed as shown in Fig. 146, although any axis of reference may be assumed. The line emf (E_{ab}) at the generator equals the vector sum of E_{ao} and E_{ob}. From Fig. 146 it will be seen that $E_{ab} = 2\,E_{ob}\cos 30°$ or $E_{ab} = \sqrt{3}\,E_{ob}$. Since the effective phase emf's are equal and the effective line emf's are equal it follows that in the Y connection

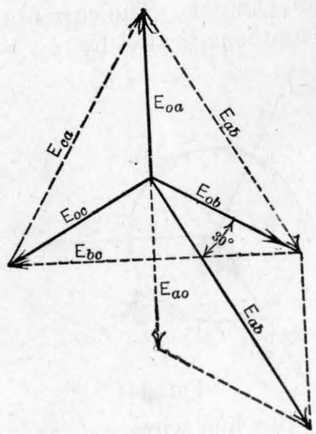


FIG. 146

121 $$E_l = \sqrt{3}\,E_p \text{ volts.}$$

The effective phase currents (I_{oa}, I_{ob}, and I_{oc}) are equal and the effective line currents ($I_{aa'}$, $I_{bb'}$, and $I_{cc'}$) are equal. Since I_{oa} equals $I_{aa'}$, for example, it follows that in the Y connection the effective line current (I_l) equals the effective phase current (I_p) or

122 $$I_l = I_p \text{ amperes.}$$

The power (P_p) converted by each phase of a Y-connected generator, from 105, is given by $P_p = E_pI_p\cos\theta$ where θ is the phase angle between E_p and I_p. The total power (P) converted by the generator is then given by $P = 3\,E_pI_p\cos\theta$. Substituting $\frac{E}{\sqrt{3}}$ for E_p and I_l for I_p the total power is given by

123 $$P = \sqrt{3}\,E_lI_l\cos\theta \text{ watts.}$$

It should be noted that $\cos\theta$, the power factor of the three-phase system, is the cosine of the phase angle between the phase emf or potential and the phase current and is not the cosine of the phase angle between the line emf or potential and the line current.

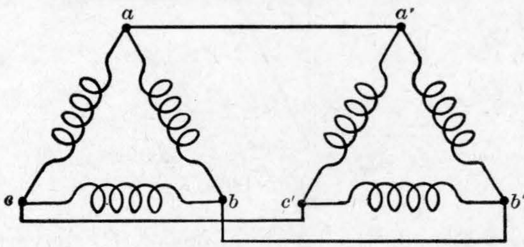


FIG. 147

The Three-phase Δ Connection. The three line emf's of a Y-connected generator are equal and differ in phase by 120 degrees as explained in the previous paragraph. If the three armature windings of a three-phase generator (*ab*, *bc*, and *ca*) are connected as shown in Fig. 147 the line emf's will also be equal and differ in phase by 120 degrees. This is called a Δ connection. The load in Figs. 145 and 147 may be either Y- or Δ-connected. The effective phase currents (I_{ab}, I_{bc}, and I_{ca}) of a Δ-connected three-phase generator supplying power to a balanced three-phase load will be equal and differ in phase by 120 degrees as shown in Fig. 148. Since the respective line emf's and phase emf's are identical it follows that in the Δ connection

124 $$E_l = E_p \text{ volts.}$$

The effective line current $I_{aa'}$, for example, equals the vector sum of the effective phase currents I_{ca} and I_{ba}. Then in Fig. 148,

$I_{aa'} = 2\, I_{ca} \cos 30°$ or $I_{aa'} = \sqrt{3}\, I_{ca}$. Since the effective phase currents are equal and the effective line currents are equal it follows that in the Δ connection

125 $$I_l = \sqrt{3}\, I_p \text{ amperes.}$$

The power (P_p) converted by each phase of a Δ-connected generator, from 105, is given by $P_p = E_p I_p \cos\theta$, where θ is the phase

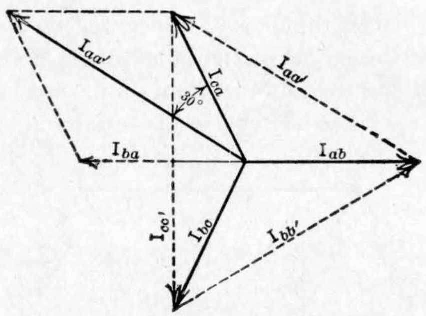


Fig. 148

angle between E_p and I_p. The total power (P) converted by the generator is then given by $P = 3\, E_p I_p \cos\theta$. Substituting E_l for E_p and $\dfrac{I_l}{\sqrt{3}}$ for I_p the total power is given by 123.

The kilovolt-amperes supplied by any three-phase generator is given by

126 $$KVA = \frac{\sqrt{3}\, E_l I_l}{1000} \text{ kilovolt-amperes.}$$

The Three-phase V and T Connections. Three-phase line emf's may be generated in an armature containing two windings located 120 degrees apart and connected as shown in Fig. 149. This is called a V connection. It will be noted that a Δ connection with one winding disconnected constitutes a V connection. The power output of the V-connected generator will not be two-thirds that of the original Δ-connected generator. In Fig. 150, for example, phase *bc* of the original Δ-connected generator is disconnected and, for the purpose of simpler analysis, the resultant V connection is replaced by a Y connection with the same line

potentials, line currents, and power factor. The vector diagram for both connections is also shown in Fig. 150.

The kilovolt-ampere rating of the original Δ-connected generator is KVA and the power factor of the load is $\cos\theta$. Then $P_{ab} =$

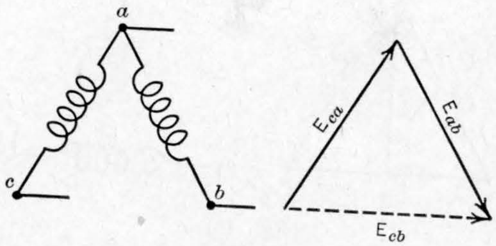


Fig. 149

$V_{ab}I_{ab} \cos (30° - \theta)$ and $P_{ac} = V_{ac}I_{ac} \cos (30° + \theta)$. Since $V_{ab}I_{ab} = V_{ac}I_{ac} = \dfrac{KVA}{3}$, the total power is given by $P = \dfrac{KVA}{3}$ $[\cos (30° - \theta) + \cos (30° + \theta)] = \frac{2}{3}\, KVA\, (\cos 30° \cos\theta)$. The

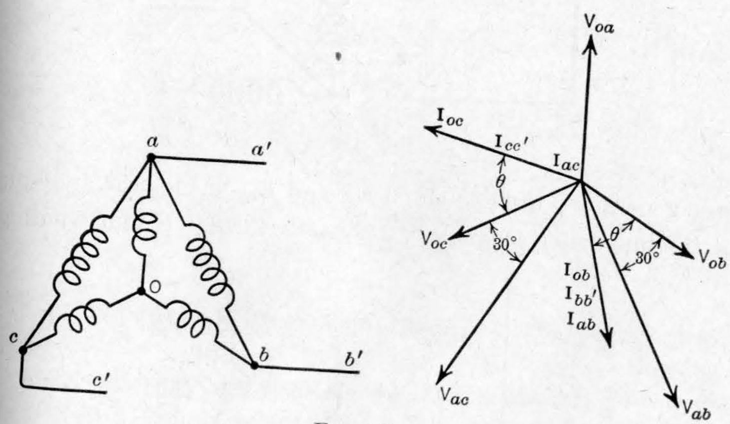


Fig. 150

maximum power output of the original Δ-connected generator at the same power factor is $KVA \cos\theta$. The rating of the V-connected generator is therefore $\frac{2}{3} \cos 30° = \frac{2}{3} \times 0.866$ or 57.7 per cent of the rating of the original Δ-connected generator.

If two windings 90 degrees apart are connected as shown in

Fig. 151 and $E_{oa} = \dfrac{\sqrt{3}}{2} E_{bc}$, the line emf's will be equal and differ in phase by 120 degrees. This is called a T connection.

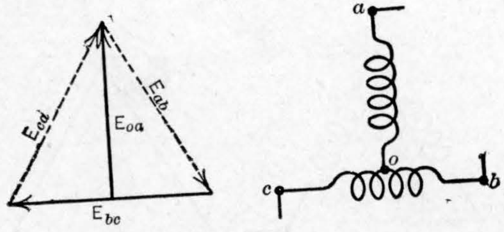


Fig. 151

Other Polyphase Connections. Two windings located 90 degrees apart in an armature (Fig. 152) will generate emf's differing in phase by 90 degrees. The generator is then called a two-

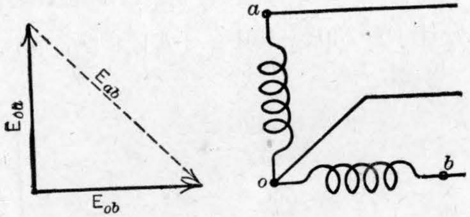


Fig. 152

phase generator; the line emf's E_{oa} and E_{ob} in Fig. 152 are equal but the line emf E_{ab} equals $\sqrt{2}\,E_{oa}$ or $\sqrt{2}\,E_{ob}$. If four windings

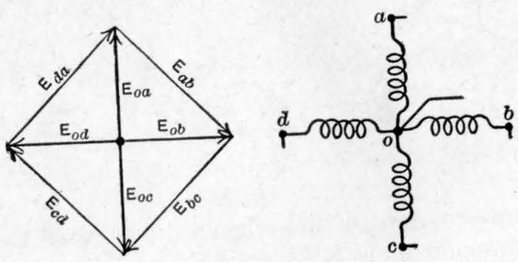


Fig. 153

located 90 degrees apart are connected as shown in Fig. 153 the generator is called a four-phase (quarter-phase) generator. In the

six-phase generator the six armature windings are located 60 degrees apart as shown in Fig. 154. Most modern alternating-current generators are Y-connected three-phase generators. Two-phase

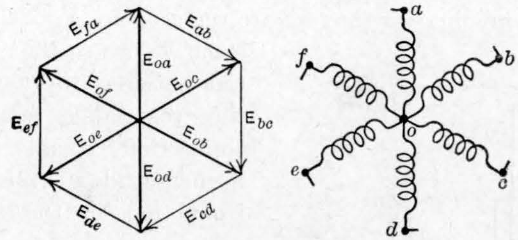


Fig. 154

and four-phase generators are employed occasionally in special cases and six-phase emf's are frequently impressed upon synchronous converters (see page 170).

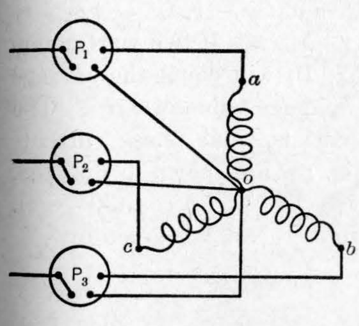


Fig. 155

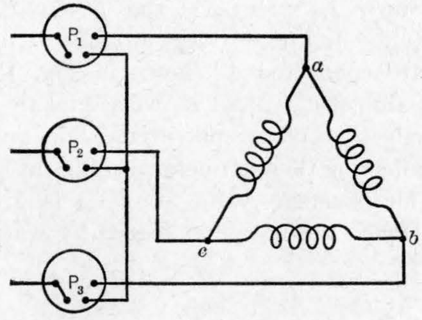


Fig. 156

Measurement of Three-phase Power by Three Wattmeters. In the three-wattmeter method the current and potential coils are connected as shown in Fig. 155 for a Y-connected load and as shown in Fig. 156 for a Δ-connected load or any other load with an inaccessible neutral. In either case the total power (P) is given by

127 $$P = P_1 + P_2 + P_3 \text{ watts.}$$

If the load is balanced the total power may be determined from the reading of a single wattmeter since $P = 3\,P_1$ or three times the power indicated by one wattmeter. In the Δ-connected load

the potential coil connection of the single wattmeter and two non-inductive connections each of the same resistance as the potential coil connection are connected in Y between a, b, and c to furnish an artificial neutral. In other words the potential coil connections of the two missing wattmeters are replaced by resistances of the same values so that the potential between the terminals of the remaining potential coil connection remains unchanged in magnitude and phase relation from that in the three-wattmeter method.

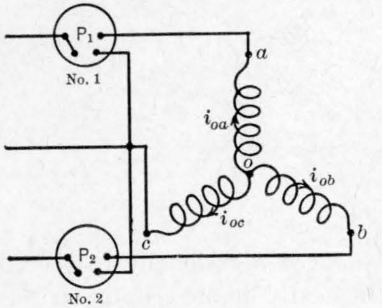


FIG. 157

The Two-wattmeter Method. The instantaneous power (p) supplied to the load shown in Fig. 157, from 7, is given by $p = v_{oa}i_{oa} + v_{ob}i_{ob} + v_{oc}i_{oc}$. Since $i_{oc} = -i_{oa} - i_{ob}$, $p = v_{oa}i_{oa} + v_{ob}i_{ob} - v_{oc}i_{oa} - v_{oc}i_{ob} = (v_{oa} - v_{oc})\, i_{oa} + (v_{ob} - v_{oc})\, i_{ob} = v_{ca}i_{oa} + v_{cb}i_{ob}$. If two wattmeters are connected as shown in Fig. 157, P_1 will equal the average value of $v_{ca}i_{oa}$ and P_2 will equal the average value of $v_{cb}i_{ob}$. The effective phase potentials, line potentials, and phase currents affecting the wattmeter readings in Fig. 157 are shown in Fig. 158. The average value of $v_{ca}i_{oa}$ is given by $V_{ca}I_{oa}\cos(30° - \theta)$. Hence the power indicated by wattmeter No. 1 is given by

128 $$P_1 = V_lI_l \cos (30° - \theta) \text{ watts.}$$

The average value of $v_{cb}i_{ob}$ is given by $V_{cb}I_{ob}\cos(30° + \theta)$. Hence the power indicated by wattmeter No. 2 is given by

129 $$P_2 = V_lI_l \cos (30° + \theta) \text{ watts.}$$

When the phase angle (θ) is not greater than 60 degrees both wattmeters will read " on scale "; that is, P_1 and P_2 are positive. When the phase angle (θ) is greater than 60 degrees (lagging current) wattmeter No. 2 will read " off scale "; that is, P_2 is negative. The total power is then given by

130 $$P = P_1 + P_2 \text{ watts}$$

where P_1 and P_2 must be substituted with the proper signs.

If the phase angle (θ) is unknown, as it usually is, connect both wattmeters so that they read " on scale." Then change the potential coil terminal of wattmeter No. 1, for example, from line c to line b. Wattmeter No. 1 will now read (see Fig. 158) $V_{ba}I_{oa}$

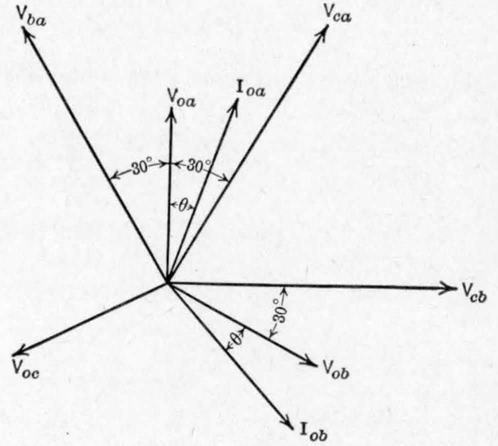


FIG. 158

$\cos(30° + \theta)$ and will read " on scale " if θ is less than 60 degrees and " off scale " if θ is greater than 60 degrees. With the former indication the total power is the sum of the original readings and with the latter indication the total power is the difference of the original readings.

Since $P_1 = V_lI_l \cos (30° - \theta)$ and $P_2 = V_lI_l \cos (30° + \theta)$ then

$$\frac{P_1 - P_2}{P_1 + P_2} = \frac{V_lI_l\,[\cos (30° - \theta) - \cos (30° + \theta)]}{V_lI_l\,[\cos (30° - \theta) + \cos (30° + \theta)]}$$

$$= \frac{2 \sin 30° \sin \theta}{2 \cos 30° \cos \theta} = \tan 30° \tan \theta = \frac{\tan \theta}{\sqrt{3}} \quad \text{and}$$

131 $$\tan \theta = \sqrt{3}\,\frac{P_1 - P_2}{P_1 + P_2} \quad \text{and}$$

132 $$\cos \theta = \frac{P_1 + P_2}{2\sqrt{P_1^2 - P_1P_2 + P_2^2}}.$$

P_1 and P_2 must be given their proper algebraic signs as indicated above.

A single polyphase wattmeter is often used in which the moving (potential) coils of each wattmeter are mounted, one above the other, on the same shaft so that a single pointer will indicate the total power when the current and potential coils are properly connected.

Practice problems with answers for Chapter VIII will be found on pages 266 to 269.

CHAPTER IX

THE ALTERNATING-CURRENT TRANSMISSION LINE

Choice of System and Potential. The power transmitted by a single-phase transmission line, Fig. 159 (*a*), is given by $P = VI \cos \theta$ and the power transmitted by a three-phase transmission line, Fig. 159 (*b*), is given by $P = \sqrt{3}\, VI' \cos \theta$. For the same power transmitted by each line $VI \cos \theta = \sqrt{3}\, VI' \cos \theta$ and $I' = \frac{I}{\sqrt{3}}$. The power converted into heat in the single-phase transmission

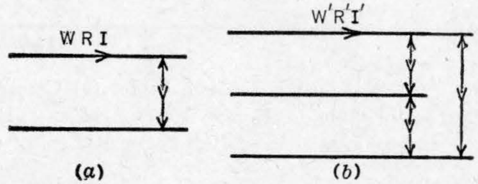
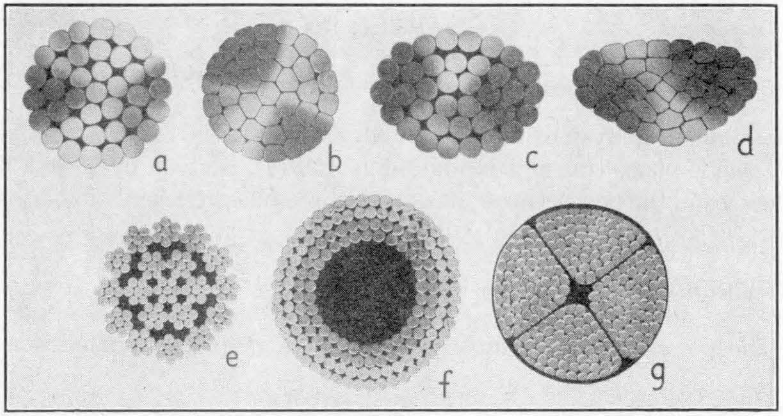


FIG. 159

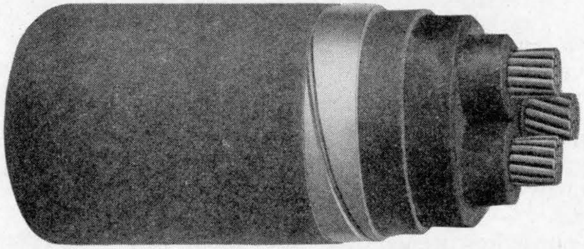
line is given by $P = 2\, I^2R$, where R is the resistance of each line wire. The power converted into heat in the three-phase transmission line is given by $P = 3\, I'^2R'$, where R' is the resistance of each line wire. Substituting $\frac{I}{\sqrt{3}}$ for I', $P = 3\, \frac{I^2}{3} R' = I^2R'$. For the same power loss in each transmission line $2\, I^2R = I^2R'$ and $R' = 2\, R$. The weight (W') of each three-phase line wire then equals one-half the weight (W) of each single-phase line wire or $W' = \frac{W}{2}$. The ratio of the total weight of the three-phase line to the total weight of the single-phase line is then $\frac{3\, W}{2} \cdot \frac{1}{2\, W}$ or 0.75. The use of a three-phase transmission line is then favored by a saving of 25 per cent of the weight of wire required in a single-phase transmission line. The total cost of a three-phase line is more than 75

per cent of the cost of a single-phase line, however, since the three-phase line requires more insulators and cross-arms, and the labor cost (stringing of three wires instead of two) is greater.



The Okonite Company.

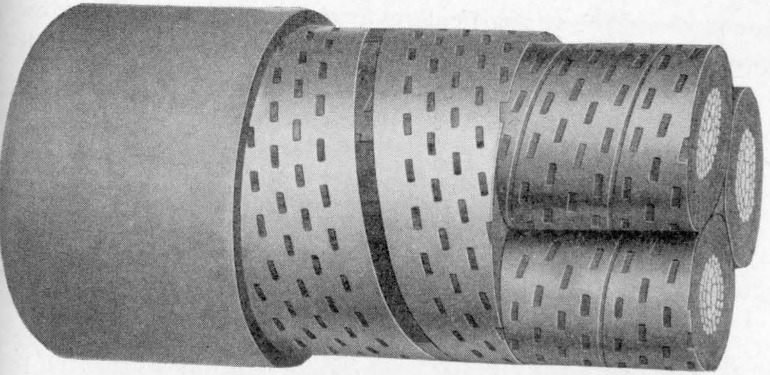
Cable Designs. (*a*) Standard concentric cable, (*b*) Compack concentric cable, (*c*) Standard sector cable, (*d*) Compack sector cable, (*e*) Rope concentric cable, (*f*) Annular (rope core) cable, and (*g*) Segmental sector cable.



Simplex Wire and Cable Co.

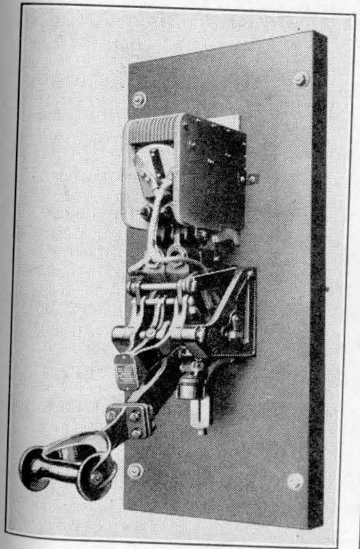
Varnished Cambric-insulated Three-conductor Cable Covered with Steel Tape.

The I^2R loss associated with the transmission of a given amount of power is inversely proportional to the square of the line potential and the line potential considered from this standpoint should be made as high as possible. An increase of line potential is accompanied, however, by an increased cost of insulators and transformers (described on page 189), increased spacing between wires resulting in an increased cost of construction, and by an increased



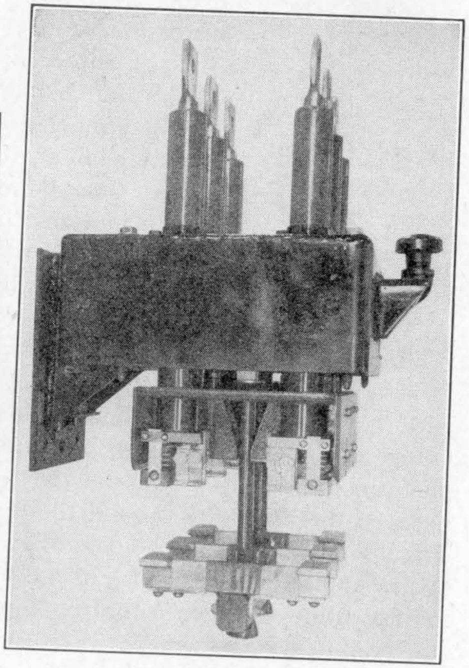
Simplex Wire and Cable Co.

Paper-insulated Three-conductor Cable with Steel Tape Shields Covered with Lead.



General Electric Co.

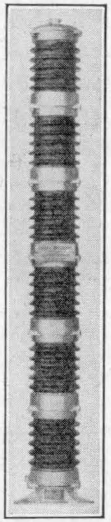
Single-pole Air Circuit Breaker.



General Electric Co.

Three-pole, Oil Circuit Breaker without Tank.

corona loss. The air, particularly at the surface of the line wires, becomes conducting under the influence of high potential gradients and small currents will flow through the air from one conductor to another throughout the entire length of the line. The corona loss is reduced by installing large diameter conductors (often hollow) with the surface as smooth as possible.



General Electric Co.

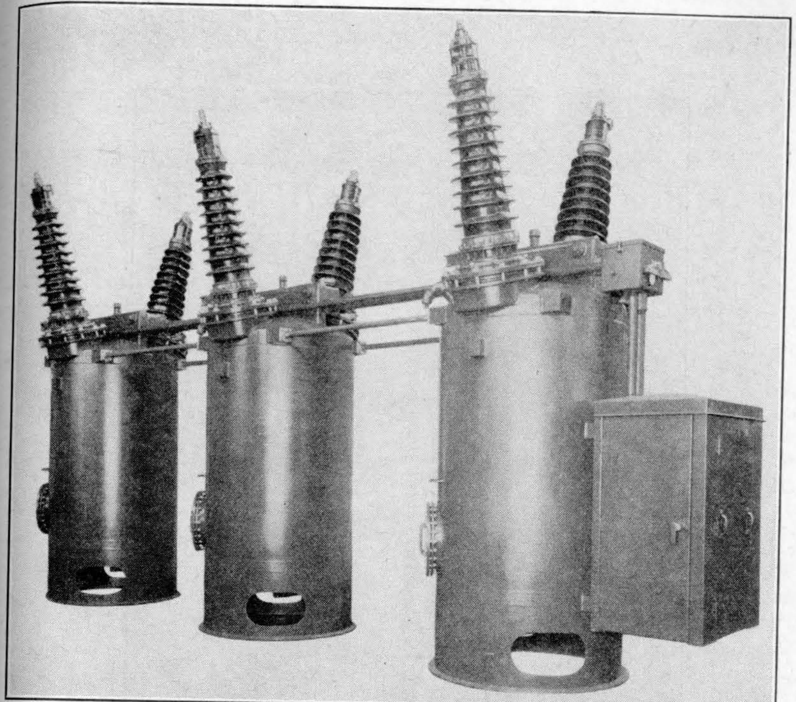
Single-pole Lightning Arrester Rated at 73 Kilovolts.

In high-voltage underground construction, which is employed only in congested places, conductors of $\frac{1}{2}$ to 1 inch in diameter are supported and insulated in conduits or in lead sheaths by paper insulated with dry mineral oil. No insulation is used in overhead construction except for secondary distribution systems at 2 or 3 kilovolts where wires are closely spaced and may swing together in the wind. The maximum potential at the moment is 287.5 kilovolts for overhead lines and 220 kilovolts for underground.

Transmission Line Calculations. The size of wire adopted in any case should be governed by Kelvin's law (see Formula 34), by the relevant mechanical conditions (the tension in the wire depends upon the distance between towers, ice loading, and wind pressure), and by the allowable difference in the line potentials at the generator and load ends of the line. The vector diagram of a single-phase transmission line is shown in Fig. 160, where I_l is the line current, R_l is the line resistance (both wires), X_l is the line inductive reactance (both wires), V_L is the line potential at the load, V_G is the line potential at the generator, θ_L is the phase angle between the line potential and the line current at the load, and θ_G is the phase angle between the line potential and the line current at the generator. The line resistance may be determined from a wire table and the line reactance from ωL (L is given per mile per wire by 55). The line potential at the generator from Fig. 160 is then given by

133 $$V_G = \sqrt{(V_L \cos \theta_L + I_l R_l)^2 + (V_L \sin \theta_L + I_l X_l)^2} \text{ volts.}$$

It should be noted that the sign of sin θ_L is negative if the line current leads the line potential at the load as in Fig. 161.



General Electric Co.

Three-phase Oil Circuit Breaker.

It should also be noted that when the line current leads the line potential at the load as in Fig. 161 the line potential at the load may be greater than the line potential at the generator. This effect is also realized in a long transmission line operated without

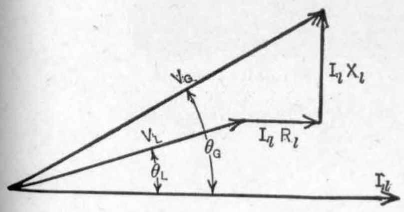


FIG. 160

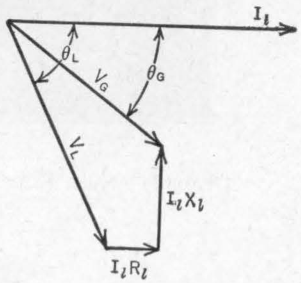
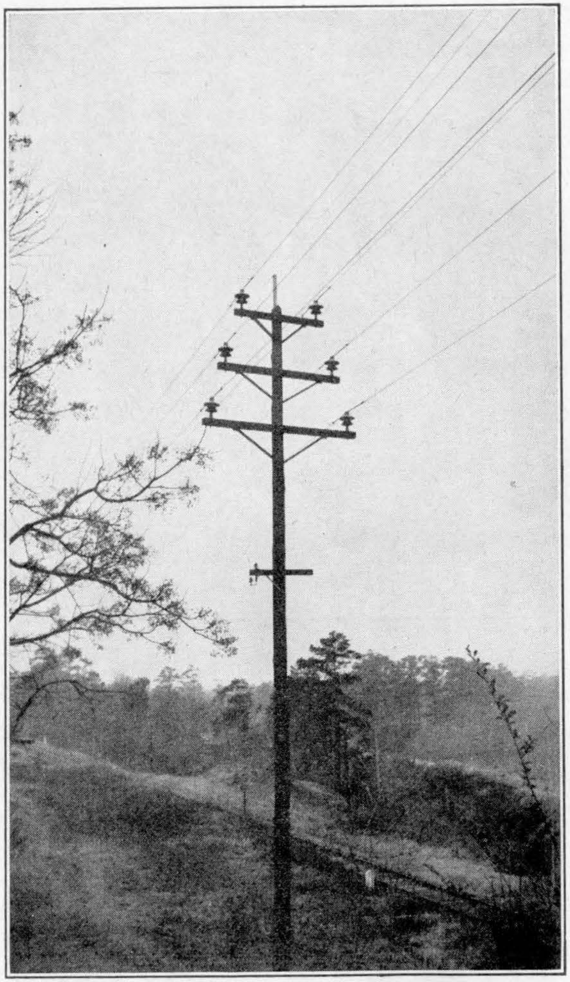
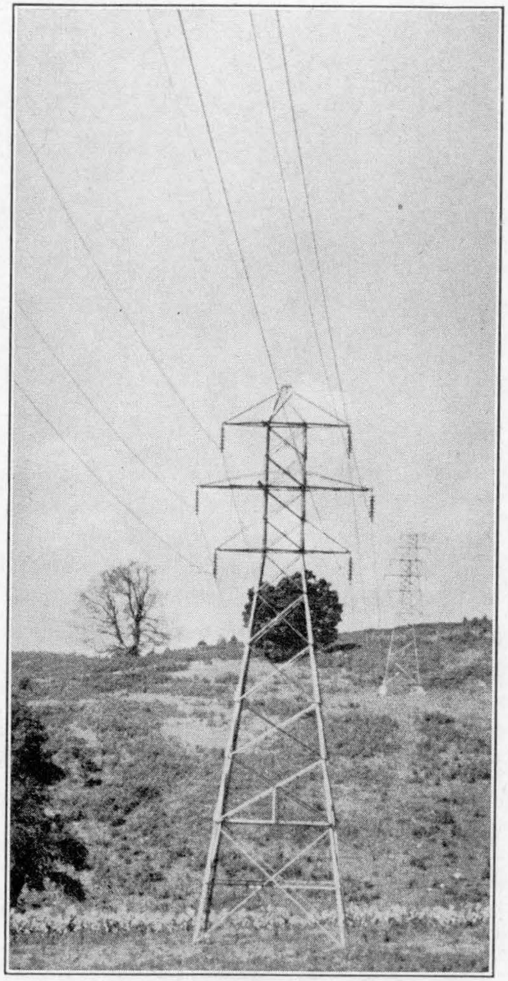


FIG. 161



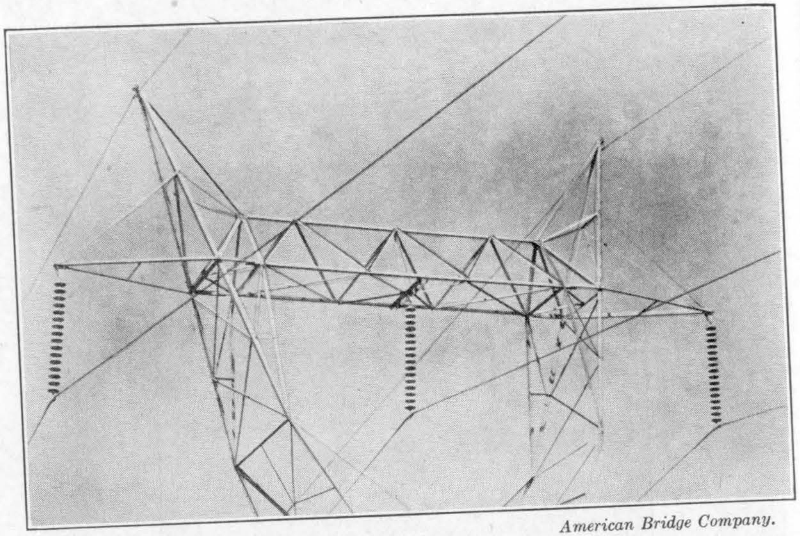
Ohio Brass Company.

Double-circuit, Three-phase, Pin-type Transmission Line.



Locke Insulator Corporation.

Double-circuit, Three-phase, Suspension-type Transmission Line.



American Bridge Company.

Detail of Single-circuit, Three-phase Suspension-type Transmission Line.

load since the transmission line wires and the intervening medium form a condenser. The capacitance of the condenser being distributed throughout the length of the line, the line current will be greatest at the generator end and zero at the load end of the line. The exact solution in this case must therefore take into account the distributed capacitance of the line.

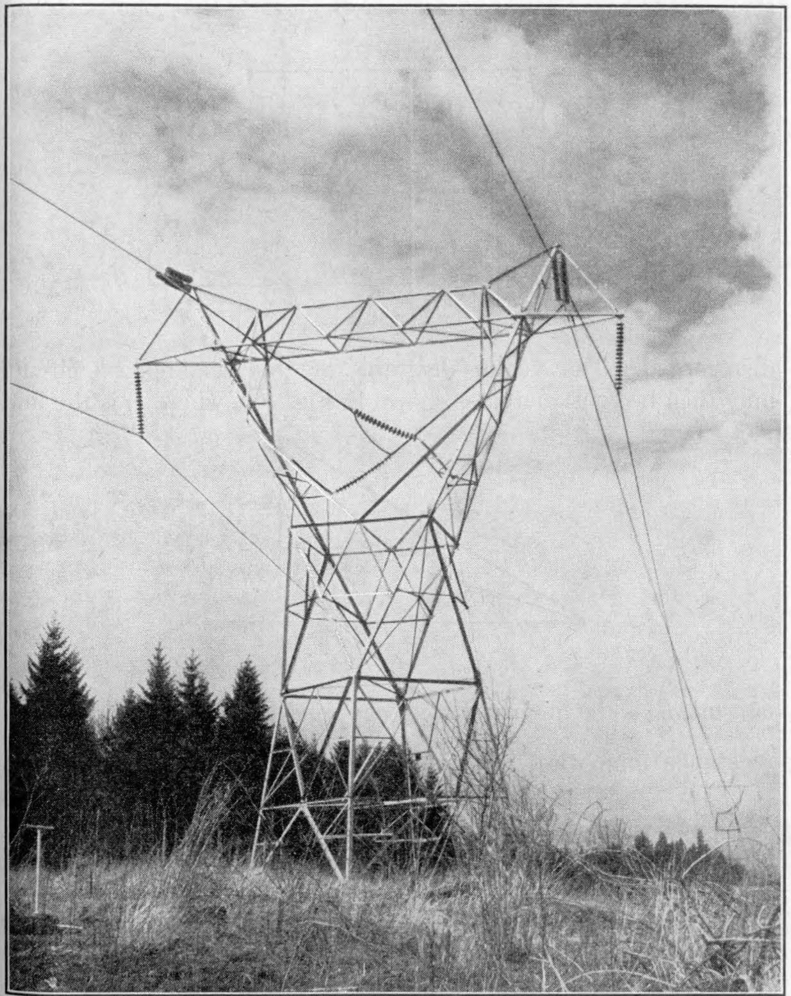
The power factor ($\cos \theta_G$) at the generator end of a single-phase transmission line, from Fig. 160 or Fig. 161, is given by

134 $$\cos \theta_G = \frac{V_L \cos \theta_L + I_l R_l}{V_G}.$$

The efficiency (η) of a single-phase transmission line is given by

135 $$\eta = \frac{V_L I_l \cos \theta_L}{V_L I_l \cos \theta_L + I_l^2 R_l}.$$

Three-phase potential calculations are made with the assumption that the generator and load are Y connected as shown in Fig. 162. Since the potential between o and o', the respective neutral points of the generator and load, is zero by symmetry a



American Bridge Company.

Single-circuit, Three-phase, Suspension-type Transmission Line Showing Transposition of Conductors to Reduce Induced Emf's in Communication Systems.

conductor of zero resistance and reactance may be assumed to be connected between o and o'. Calculations may then be made for the single-phase circuit ($oaa'o'o$), the other two phases being

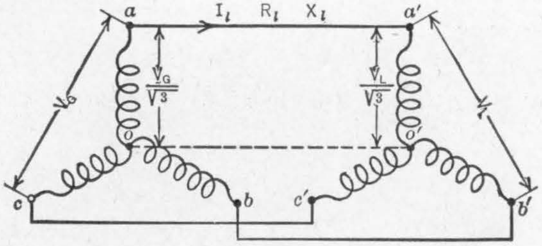


FIG. 162

disregarded. The vector diagram for this single-phase circuit may then be constructed as shown in Fig. 163, where I_l is the line

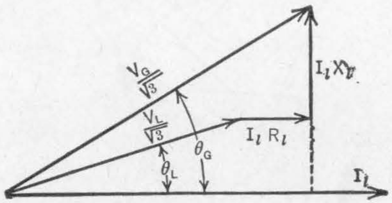
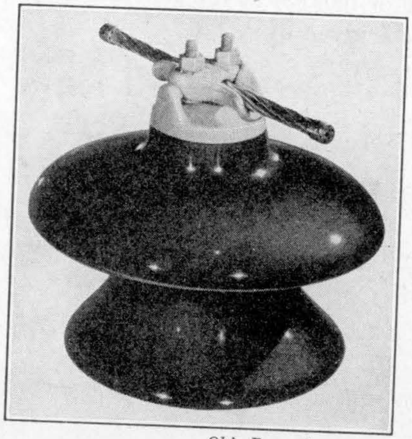


FIG. 163

current, R_l is the line resistance (one wire), X_l is the line inductive reactance (one wire), $\frac{V_L}{\sqrt{3}}$ is the Y-phase potential at the load, $\frac{V_G}{\sqrt{3}}$ is the Y-phase potential at the generator, θ_L is the phase angle between the Y-phase potential and the line current at the load and θ_G is the phase angle between the Y-phase potential and the line current at the generator. The line potential (V_G) at the generator, from Fig. 163, is then given by

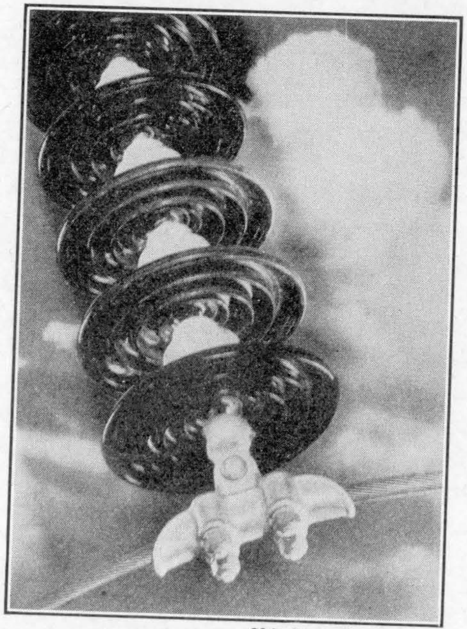
$$136 \quad V_G=\sqrt{3}\sqrt{\left(\frac{V_L}{\sqrt{3}}\cos\theta_L+I_lR_l\right)^2+\left(\frac{V_L}{\sqrt{3}}\sin\theta_L+I_lX_l\right)^2}\ \text{volts.}$$

The sign of $\sin\theta_L$ is negative if the line current leads the Y-phase potential at the load.



Ohio Brass Company.

Detail of Pin-type Insulator.



Ohio Brass Company.

Detail of Suspension-type Insulator.

The power factor ($\cos \theta_G$) at the generator end of a three-phase transmission line is given by

$$\cos \theta_G = \frac{\dfrac{V_L}{\sqrt{3}} \cos \theta_L + I_l R_l}{\dfrac{V_G}{\sqrt{3}}}. \tag{137}$$

The efficiency (η) of a three-phase transmission line is given by

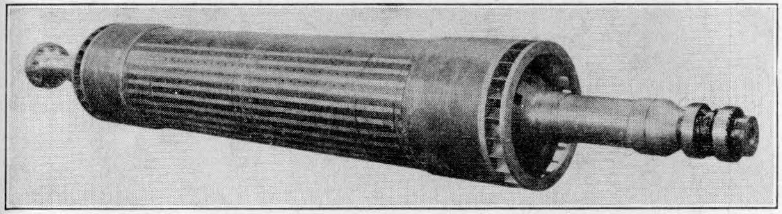
$$\eta = \frac{\sqrt{3}\, V_L I_l \cos \theta_L}{\sqrt{3}\, V_L I_l \cos \theta_L + 3\, I_l^2 R_l}. \tag{138}$$

Practice problems with answers for Chapter IX will be found on pages 269 to 271.

CHAPTER X

THE SYNCHRONOUS GENERATOR

Construction. The synchronous generator contains an armature with a single-phase or polyphase winding and a magnetic field excited by a separate source of direct current. The armature winding may be endless (as in a direct-current dynamo) but is



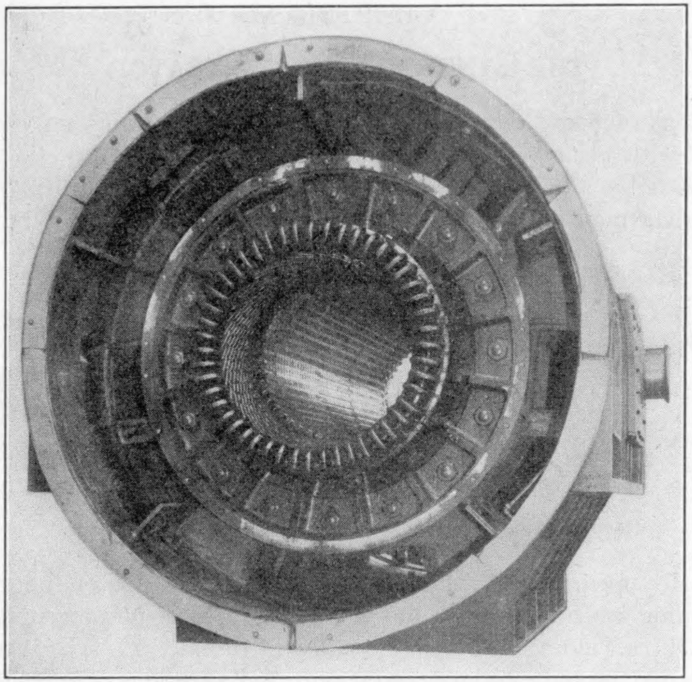
General Electric Co.

Revolving Field of a Three-phase Synchronous Generator.

usually open. In a single-phase generator the ends of the open winding are connected to the line and in a three-phase generator the three windings are Δ or Y connected (usually Y). The armature may be stationary or revolving (usually stationary for generators of more than 500 kilovolt-amperes capacity). Among the advantages of the stationary armature are the opportunity for installing better insulation, more thorough cooling (by forced ventilation), and more substantial terminal connections to the line. A revolving field may also be constructed to withstand higher centrifugal stresses than a revolving armature. The windings of a revolving armature are connected to the line through two or more slip rings and a revolving field winding is connected to its source of excitation in the same manner.

Large rotating electrical machines, particularly synchronous generators, are sometimes completely enclosed by a steel tank filled with hydrogen gas. The windage loss, due to the lower density of the hydrogen, is about 10 per cent of the loss with air.

The maximum rating of generators may be increased as much as 20 per cent due to the superior cooling properties of the hydrogen. The life of insulation is increased due to the absence of oxidation



General Electric Co.

Stationary Armature of a Three-phase Synchronous Generator.

and reduced corona. Air being excluded from the tank there is no fire hazard and with the heavy housing as a sound insulator the unit as a whole operates more quietly.

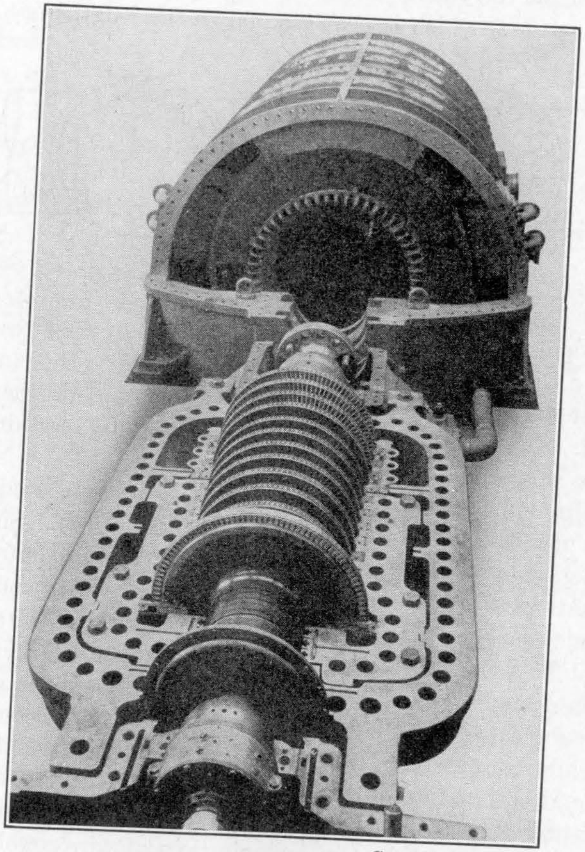
The frequency of a synchronous generator equals the product of the number of poles (p) and the speed (S) in revolutions per minute divided by 120. The speed of a synchronous generator must therefore be maintained constant and is given conversely by

139 $$S = \frac{120\,f}{p} \text{ revolutions per minute.}$$

The maximum speed of a 60-cycle generator is then $\frac{120 \times 60}{2}$,

or 3600 rpm, and for a 25-cycle generator $\frac{120 \times 25}{2}$, or 1500 rpm.

Emf Generated by a Synchronous Generator. The maximum emf generated in the armature of a single-phase generator



General Electric Co.

Turbine Rotor and Stationary Armature of a Three-phase Synchronous Generator.

when all the armature slots are filled with conductors equals the vector sum of the maximum emf's generated in the various conductors. Since the emf's generated in two adjacent conductors differ in phase by the subtended angle the individual emf's may

be represented by vectors of equal length drawn tangent to the surface of the armature. The vector sum of the individual emf's is then represented to scale by the diameter of the armature (*ab* in Fig. 164). It will be noted that if the slots adjacent to *a* and *b* are left vacant the emf generated in the armature is proportional to the length (*cd*) which is nearly equal to the length (*ab*). It is

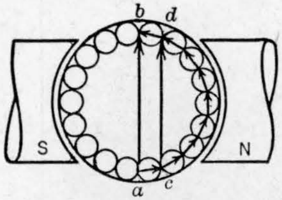


FIG. 164

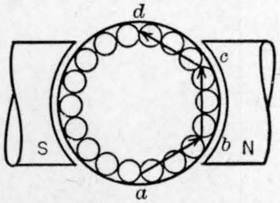


FIG. 165

then evident that the conductors in the slots adjacent to *a* and *b* should be eliminated since they contribute little to the emf of the generator and increase the armature resistance and reactance if included. It is for this reason that approximately one-third of the slots of a single-phase armature are left vacant.

In a three-phase armature (Fig. 165) the emf generated in each phase is proportional to the length (*ab*), (*bc*), and (*cd*). Since each phase belt extends over a smaller portion of the circumference of the armature all the armature slots may be filled with conductors. In a single-phase generator the entire circumference of the armature may not be used effectively and its armature must therefore be larger in diameter than the armature of a three-phase generator of the same capacity. The single-phase generator in consequence weighs approximately 30 per cent more than the three-phase generator and is therefore more expensive.

Armature Reaction in Synchronous Generators. If the alternating current established in a single turn of wire revolving at a speed of ω radians per second is in phase with the emf generated in the single turn the mmf due to the alternating current at any instant is given by $f = \mathcal{F}_m \sin \omega t$, where $\mathcal{F}_m$ is the maximum mmf due to the current. The mmf along the axis (XX') in Fig. 166 acting in conjunction with the field mmf is then given by $f = \mathcal{F}_m \sin \omega t \cos \omega t = \mathcal{F}_m \dfrac{\sin 2\,\omega t}{2}$. The mmf due to the armature

current at any instant along the axis (XX') plotted with the emf generated in the rotating coil at the same instant for comparison is shown in Fig. 167. It will be noted that the frequency of the mmf due to the armature current along the axis (XX') is twice that of the generated emf and that this mmf successively aids and opposes the field mmf. The variation of the armature mmf in a single-phase generator with a concentrated or distributed winding is the same as that shown in Fig. 167, the magnitude of the mmf being less however in the distributed winding than in the concentrated winding. The magnetic flux produced by the armature mmf is alternating and the hysteresis and eddy-current loss in the

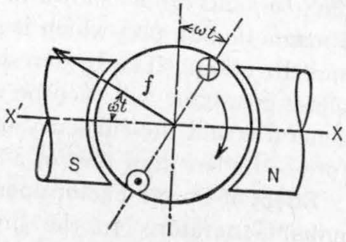


FIG. 166

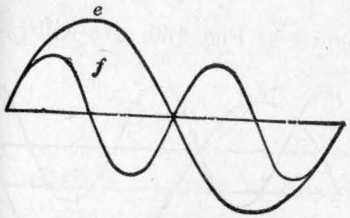


FIG. 167

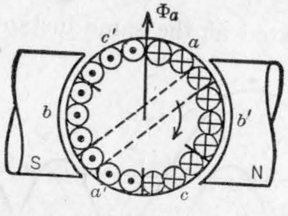


FIG. 168

armature core due to the rotation of the armature in the magnetic flux produced by the field mmf is therefore augmented by the alternating flux produced by the armature mmf. The magnetic flux in the field poles produced by the armature mmf is an alternating flux of twice the frequency of the armature current and therefore produces a large hysteresis and eddy-current loss in the field poles.

If several independent single turns are wound upon an armature as shown in Fig. 168 and the emf and current in each turn are in phase the sum of the currents and their directions on each side of the interpolar plane at any instant will be constant. The magnetic flux due to these armature currents will then be constant in magnitude and direction. Since the direction of this flux (Φ_a) is perpendicular to the flux due to the field mmf it will neither aid nor

oppose the field flux but will distort the flux through the armature and reduce its magnitude by saturating the leading pole tips. The conductors in a three-phase armature are connected in groups (aa', bb', and cc') as shown in Fig. 168 and will therefore produce a magnetic flux (Φ_a) which is substantially constant in magnitude and direction. The hysteresis and eddy-current loss in a three-phase generator will then be much smaller than in a single-phase generator and the efficiency of a three-phase generator will therefore be higher than that of a single-phase generator.

Effect of Power Factor upon the Generated Emf of a Synchronous Generator. In the single-phase generator (Fig. 166) the armature mmf at any instant along the axis (XX') when the armature current lags the generated emf by θ degrees is given by $f = \mathcal{F}_m \sin (\omega t - \theta) \cos \omega t = \frac{\mathcal{F}_m}{2} (\sin (2\,\omega t - \theta) - \sin \theta)$ $= \frac{\mathcal{F}_m}{2} \sin (2\,\omega t - \theta) - \frac{\mathcal{F}_m}{2} \sin \theta$. This mmf plotted with the emf generated at the same instant is shown in Fig. 169. It will be

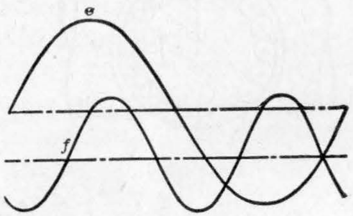


FIG. 169

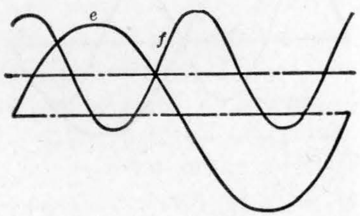


FIG. 170

noted that when θ equals zero (Fig. 167) the successive magnetizing and demagnetizing effects of the armature current are equal but that the demagnetizing effect with a lagging current (Fig. 169) is greater than the magnetizing effect. When the armature current leads the generated emf by θ degrees $f = \mathcal{F}_m \sin (\omega t + \theta) \cos \omega t$ $= \frac{\mathcal{F}_m}{2} (\sin (2\,\omega t + \theta) + \sin \theta) = \frac{\mathcal{F}_m}{2} \sin (2\,\omega t + \theta) + \frac{\mathcal{F}_m}{2} \sin \theta$. This mmf plotted with the emf generated at the same instant is shown in Fig. 170. It will be noted that with a leading armature current the magnetizing effect of the armature current is greater than the demagnetizing effect. The net armature flux and the generated

emf in consequence, is therefore weakened by a lagging current and strengthened by a leading current.

In a three-phase generator the plane of the flux (Φ_a) due to the armature currents will be turned in the direction of rotation through an angle (θ) when the current in each phase lags the phase emf by θ degrees, as shown in Fig. 171, and will be turned in the opposite direction through an angle (θ) when the phase current leads the phase emf by θ degrees. A lagging current then produces a demagnetizing effect and a leading current a magnetizing effect in the three-phase generator. The generated emf will therefore be decreased by a lagging current and increased by a leading current.

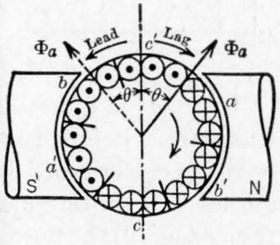


FIG. 171

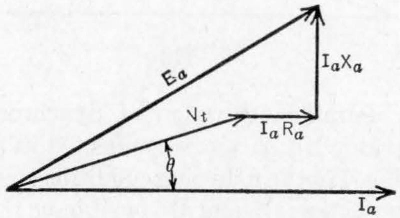


FIG. 172

Relation between Generated Emf and Terminal Potential. The vector diagram for a single-phase generator is shown in Fig. 172. E_a is the generated emf, V_t is the terminal potential, I_a is the armature current, θ is the phase angle between the terminal potential and the armature current, R_a is the armature resistance, and X_a is the armature inductive reactance. The generated emf, from Fig. 172, is then given by

140 $$E_a = \sqrt{(V_t \cos \theta + I_a R_a)^2 + (V_t \sin \theta + I_a X_a)^2} \text{ volts.}$$

The sign of $\sin \theta$ is negative if the armature current leads the terminal potential.

The vector diagram for one phase of a three-phase generator is shown in Fig. 173. E_p is the generated phase emf, V_p is the phase potential, I_p is the phase current, θ is the phase angle between the phase potential and the phase current, R_p is the phase resistance, and X_p is the phase inductive reactance. The generated phase

emf, from Fig. 173, is then given by

141 $$E_p = \sqrt{(V_p \cos\theta + I_pR_p)^2 + (V_p \sin\theta + I_pX_p)^2} \text{ volts.}$$

In a Δ-connected generator $E_l = E_p$, and in a Y-connected generator $E_l = \sqrt{3}\, E_p$. Sin θ is negative if I_p leads V_p.

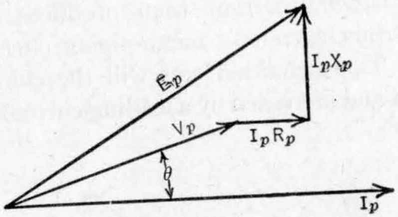


FIG. 173

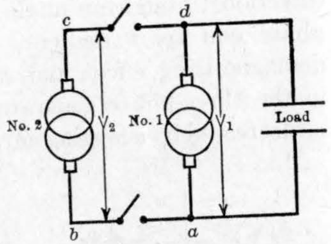


FIG. 174

Parallel Operation of Synchronous Generators. Before generator No. 2 can be connected in parallel with generator No. 1 in Fig. 174 the following conditions must be satisfied: (1) the terminal potentials, V_1 and V_2, must have the same frequency, (2) the terminal potentials must differ in phase by 180 degrees in the circuit *abcda*, (3) the terminal potentials must be equal, and (4), the terminal potentials must have the same wave form. If any one of these conditions is not satisfied current will flow from one generator through the other when the switch is closed. When all four conditions are satisfied the generators are said to be in synchronism. Any device connected across the open switch that will indicate the current flowing in the circuit *abcd* may be employed to synchronize the two generators.

In the dark lamp method incandescent lamps are connected across the open single-phase switch as shown in Fig. 175 (*a*). If the generators are not in synchronism the lamps will either burn steadily or flicker. The speed and terminal potential of each generator must then be adjusted until the lamps remain dark; the switch may then be closed. The connections of the lamps for synchronizing three-phase generators by the dark lamp method are shown in Fig. 175 (*b*). In the bright lamp method the lamps are connected as shown in Fig. 175 (*c*) for a single-phase switch and in Fig. 175 (*d*) for a three-phase switch. In this case synchronism of single-phase generators is indicated when the lamps

burn brightest and do not flicker. Synchronism of three-phase generators by the bright lamp method is indicated when one lamp is dark and the other two lamps are equally bright. The dark lamp method in general is not as dependable as the bright lamp method because a lamp may burn out during the synchronizing

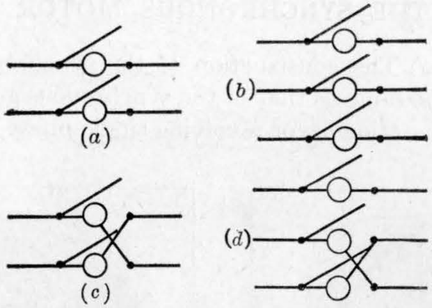


FIG. 175

period and deceive the operator. The dark lamp method also is not as accurate because an incandescent lamp remains dark with considerable potential between its terminals. A bright lamp on the other hand indicates very accurately the time when the potential across its terminals is a maximum. An instrument called a synchroscope, or a synchronism indicator, may be connected between the generator to be synchronized and the busbars. The slow rotary motion of a pointer on the instrument indicates whether the generator to be synchronized is running too fast or too slow. Synchronism is indicated when the pointer remains stationary in a vertical position.

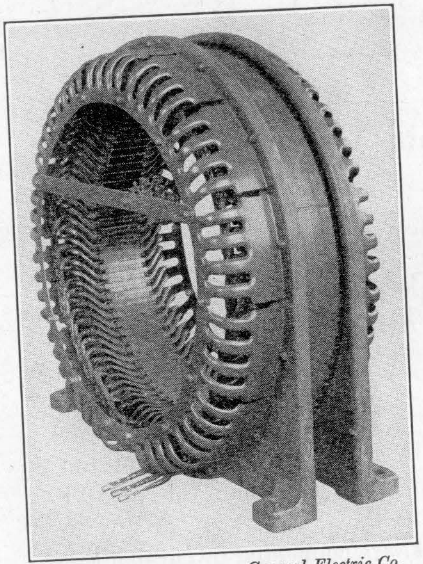
After the two generators (Fig. 174) are connected in parallel the load may be distributed between the two generators by regulating the mechanical power input to each generator (admit more or less steam to a steam turbine for example) and by adjusting the generated emf's of the two generators. The adjustment of the generated emf's alone will effect no change in the power supplied by each generator but will change the power factor of each generator. The mechanical power input and the generated emf of each generator should be adjusted until each generator supplies its proportion of the total load and the power factor of each generator is the same and equal to the load power factor.

Practice problems with answers for Chapter X will be found on pages 272 to 273.

CHAPTER XI

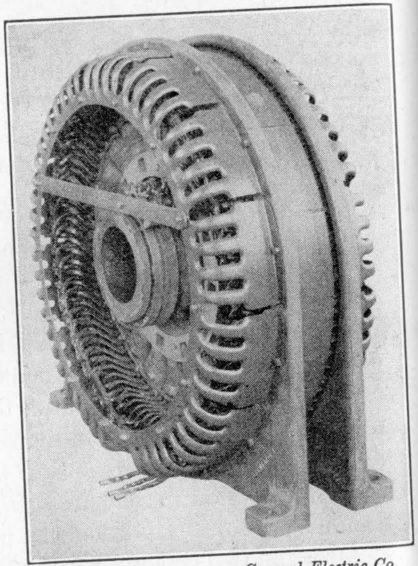
THE SYNCHRONOUS MOTOR

Construction. The construction of the synchronous motor is substantially the same as that of the synchronous generator; that is, it contains a stationary or revolving single-phase or three-phase



General Electric Co.

Stationary Armature of a Three-phase Synchronous Motor.



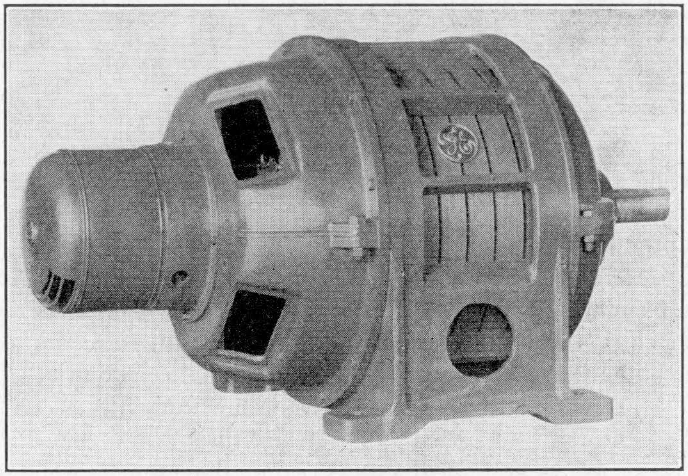
General Electric Co.

Three-phase Synchronous Motor with Revolving Field.

armature and a magnetic field excited by a separate source of direct current. Since it usually operates at slower speed it is larger and has more poles than a synchronous generator of the same capacity.

Starting Conditions. If an alternating current is established in an armature winding located in a magnetic field of fixed direction as shown in Fig. 176 the armature torque is alternating, clockwise

for the direction of current shown in Fig. 176 and counterclockwise during the next half-cycle. There is therefore no net torque in either direction and the synchronous motor is not self-starting. If the armature (or the field, as the case may be) is rotated by an auxiliary motor at a speed of $\frac{120\,f}{p}$ revolutions per minute and the emf generated in the motor armature is made equal and opposite



General Electric Co.

Three-phase Synchronous Motor with Direct-connected Exciter.

to the line potential at any instant the alternating current established in the armature winding when the line switch is closed and the auxiliary motor is disconnected will change in direction synchronously with respect to the poles so that the direction of the armature torque will remain constant. It will be noted, in Fig. 177, that the armature has turned 180 degrees from the position shown in Fig. 176 and since the current has also reversed in direction the torque is still clockwise. The torque of a single-phase motor will be pulsating but in a three-phase motor the torque will be nearly constant. In starting a synchronous motor synchronism may be indicated by the dark or bright lamp method or by the synchroscope employed in synchronizing generators operated in parallel. After the synchronous motor is synchronized and con-

nected to the line the auxiliary motor may be disconnected electrically or mechanically. The synchronous motor will then rotate under its own torque at constant speed (given by 139). The

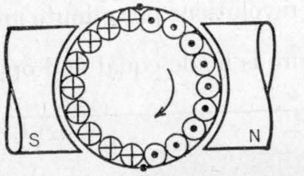


FIG. 176

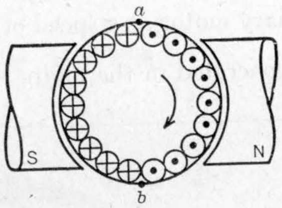


FIG. 177

starting of a three-phase synchronous motor at no load as an induction motor without the auxiliary motor will be discussed in Chapter XV.

The Effect of Changing the Load on a Synchronous Motor. The terminal potential (V_t) of a single-phase synchronous motor must equal the vector sum of the generated emf (E_a), the resistance potential (I_aR_a), and the inductive reactance potential (I_aX_a) as shown in Fig. 178. For the three-phase motor the same diagram may be constructed substituting V_p for V_t, E_p for E_a, I_pR_p for I_aR_a, and I_pX_p for I_aX_a. An increase of load will cause the armature to slow down momentarily and then continue to rotate at the same constant speed as before. Each conductor on the armature will then pass a given point on a pole face a little later than it did before the load was increased. The generated emf, while unchanged in magnitude except through the effect of armature reaction, will then lag the terminal potential by a greater angle as shown by the dotted vector in Fig. 178. The armature current will then be readjusted in magnitude and phase until the power input to the motor equals the power output plus the losses. In a direct-current shunt motor, for comparison, an increase in load reduces the speed and the generated emf (in consequence), and

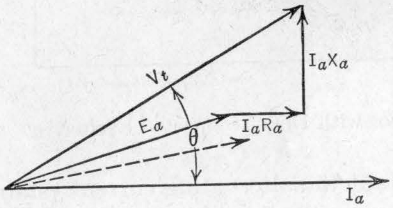


FIG. 178

increases the armature current. In the synchronous motor a permanent change in speed is impossible so that an increase in the power input required by an increase in load must be obtained by a shift in phase between the generated emf and the terminal potential with a consequent increase in the armature current.

If changes in the load, or changes in the frequency of the source of electrical power, become regular and continuous, the rotor of the synchronous motor may be set into undesirable vibration, called "hunting." For the same reason the sudden application of a heavy load may cause the rotor to drop out of synchronism and come to rest. The reduction of the effects of "hunting" in synchronous motors will also be discussed in Chapter XV.

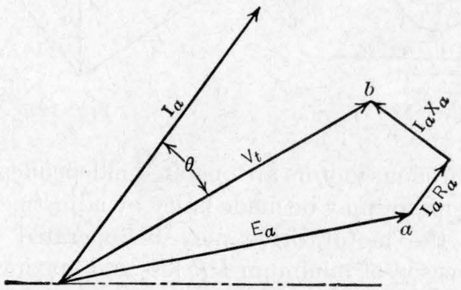


FIG. 179

The Effect of Changing the Excitation of a Synchronous Motor. If the excitation of a synchronous motor operating under the conditions shown in Fig. 178 is increased the generated emf must increase and the electrical conditions will then be represented by the vector diagram shown in Fig. 179, where V_t is referred to the same axis of reference as in Fig. 178. The ratio of the potentials, I_aX_a and I_aR_a, being fixed by the ratio of X_a to R_a, only one reactance-resistance potential triangle may be drawn between a and b for the existing operating conditions in the motor. Since I_a is always parallel to I_aR_a, a sufficient increase in the generated emf will force the armature current into the position shown in Fig. 179. The power factor of a synchronous motor may thus be controlled by adjustment of the field current. Since the current supplied to the motor depends upon the power factor for a given load the magnitude of the armature current will also depend

upon the field current. A plot of the armature current and the field current of a synchronous motor at full load and half load (called the V curves of a synchronous motor) is shown in Fig. 180. On the full load curve, for example, the speed being constant, the torque is constant at all points on the curve. A constant torque with variable armature current is explained by inverse changes in air-gap flux due to armature reaction.

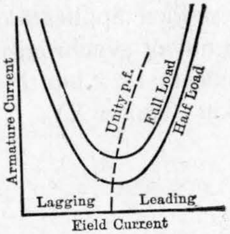


FIG. 180

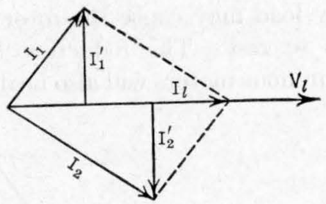


FIG. 181

When synchronous motors are operated independently the power factor of each motor may be made unity by adjustment of the field current, and the motor drive may be operated at maximum economy by reason of minimum I^2R loss and maximum use of the capacity of the motors, line wires, transformers, and generators. Since the current for a given load is a minimum at unity power factor, changes of terminal potential due to changes in load (called the voltage regulation) will be a minimum. If one or more synchronous motors are connected in parallel with other motors which operate under a lagging power factor not subject to control, the field current of the synchronous motors may be adjusted until the wattless component (I_1') of the leading synchronous motor current equals the wattless component (I_2') of the lagging current supplied to the other motors. The line current (I_l) in Fig. 181 will then be in phase with the line potential (V_l) (or the Y-phase potential of a three-phase line) and the system will be operated at unity power factor. A synchronous motor used for this purpose (correction of power factor) is sometimes called a synchronous condenser and may either supply mechanical power or be operated under no load. Static condensers are often used in place of synchronous motors to accomplish the same effect.

The Electric Clock. Synchronous motors of two types are operated in electric clocks on alternating-current systems and give accurate time at little expense. In the self-starting motor shown in Fig. 182, the shaft of the rotor (*R*), stamped from a single sheet of soft steel, is connected by a double worm gear to the hands of the clock. When the stationary armature winding (*WW*) on the laminated field poles (*PP*) is connected to a 60 cps alternating-current circuit an alternating flux passes horizontally through the rotor and also through the heavy copper rings (*R′R′*) in the " shaded " pole slots. The alternating currents induced in

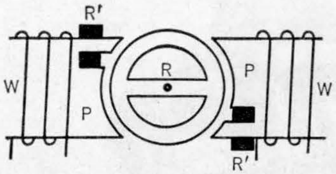


FIG. 182

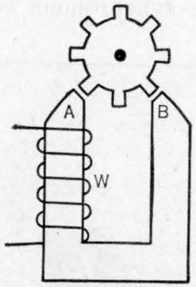


FIG. 183

the rings produce an alternating flux which, combined with the main flux, establishes a rotating flux which starts the motor as explained in Chapter XV. As the rotor comes up to speed it becomes polarized (*N* and *S*) and jumps into synchronism (3600 rpm). Interruption of current causes the rotor to coast down to rest. It is demagnetized on the way by the small residual magnetism in the laminated field poles and will start again when service is restored.

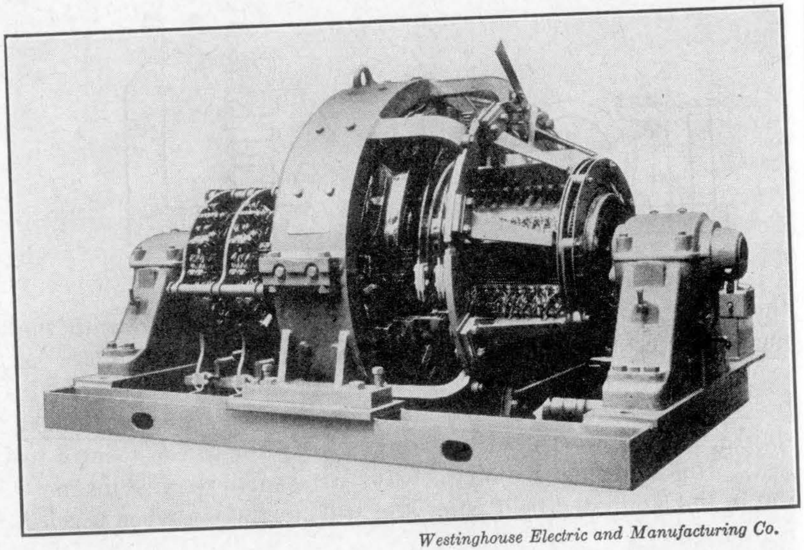
In the " phonic " motor a laminated soft iron wheel with square teeth, as shown in Fig. 183, must be spun above synchronism after the winding (*W*) on a laminated iron core is connected to a 60 cps alternating-current circuit. The polarity at *A* and at *B* reverses every 1/120 of a second and, as the wheel tends to drop below synchronism, pulls the nearest tooth and the wheel into synchronism. Synchronous speed is 7200 rpm divided by the number of teeth. The hands of the clock are driven by gears of proper reduction.

Practice problems with answers for Chapter XI will be found on pages 273 to 275.

CHAPTER XII

THE SYNCHRONOUS CONVERTER

Construction. A synchronous converter is similar in construction to a shunt or compound direct-current generator with the addition of two or more slip rings connected to the armature winding. The synchronous converter then consists of a revolving



Westinghouse Electric and Manufacturing Co.

Six-phase Synchronous Converter.

drum-wound armature with a commutator and slip rings, and a shunt or compound field winding. The single-phase converter (rarely used) has two slip rings connected to respective points in the armature winding located 180 electrical degrees apart and the three-phase converter has three slip rings connected to respective points in the armature winding located 120 electrical degrees apart, etc.

Applications of the Synchronous Converter. In certain applications of electric power direct currents are more desirable than alternating currents; notably, in arc lighting, in electric motors requiring close speed adjustment, in electrolytic processes in which the desired chemical action depends upon the direction of the current, in most electric railway systems due to the relevant adaptation of the series direct-current motor, in motion picture projection apparatus using arc lamps, in general application to telephone systems with some exceptions, in many forms of electric arc welding, in lifting magnets, in many types of electromagnetic relays, and in the transmission of power at high potential. In the last application subsidiary apparatus is in the process of development and the potential will be higher than that attainable in synchronous converters. If a synchronous converter is synchronized and connected to an alternating-current source of power it will operate at constant speed as a synchronous motor. The rotating armature will also serve as the armature of a direct-current generator. Direct current can then be taken from the brushes on the commutator side, supplying power to a direct-current load and also furnishing excitation to the field winding. The principal use made of the synchronous converter is in this capacity; namely, to convert alternating-current power into direct-current power. The same machine may be operated as a direct-current shunt or compound motor and convert direct-current power into alternating-current power. A synchronous converter may be connected, for example, between a storage battery and an alternating-current system when conditions require the maintenance of a storage battery reserve. It may also be used to supply power to an alternating-current radio receiver from a direct-current source although a magnetic vibrator is more often employed especially in radio receivers installed in automobiles. If the armature be driven mechanically a synchronous converter may be employed to convert mechanical power into alternating- and direct-current power simultaneously and is often called a double-current generator.

Relation between the Direct Emf and the Alternating Emf Generated in a Synchronous Converter. In a single-phase synchronous converter the emf (E_{dc}) generated between the commutator brushes equals the maximum emf (E_m) generated between

the slip rings. The effective value (E_{ac}) of a sinusoidal emf generated in a single-phase converter is then given by

142 $$E_{ac} = \frac{E_{dc}}{\sqrt{2}} = 0.707\ E_{dc} \text{ volts.}$$

If the effective value of the emf generated between two diametrically opposite points on the armature winding of a synchronous

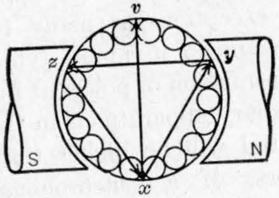


FIG. 184

converter is represented by the vector (E_{xv}) in Fig. 184 the effective value (E_{ac}) of the phase emf generated in a three-phase synchronous converter is given by $E_{ac} = \frac{E_{xy}}{E_{xv}} \cdot \frac{E_{dc}}{\sqrt{2}}$. Since $E_{xy} = \frac{\sqrt{3}}{2} E_{xv}$, $E_{ac} = \frac{\sqrt{3}}{2} \cdot \frac{E_{dc}}{\sqrt{2}}$ and the effective emf (E_{ac}) generated between the slip rings of a three-phase synchronous converter is given by

143 $$E_{ac} = \sqrt{\frac{3}{8}}\ E_{dc} = 0.612\ E_{dc} \text{ volts.}$$

The general relation between E_{ac} and E_{dc} for any number of phases is given by

144 $$E_{ac} = 0.707\ E_{dc} \sin \frac{\pi}{n} \text{ volts}$$

where n, the number of slip rings, equals two for a single-phase converter, and equals the number of phases for a polyphase converter. In a four-phase converter, for example, $E_{ac} = 0.707\ E_{dc} \sin \frac{\pi}{4}$ or $E_{ac} = 0.500\ E_{dc}$. In a six-phase converter, $E_{ac} = 0.354\ E_{dc}$, and in a twelve-phase converter, $E_{ac} = 0.183\ E_{dc}$.

Relation between the Direct Current and the Alternating Current in a Synchronous Converter. The approximate relationship of the direct and alternating current may be determined by neglecting the copper losses and rotational losses in the converter. In a single-phase converter the alternating-current power input then equals the direct-current power output and, assuming unity power factor, $E_{ac}I_{ac} = E_{dc}I_{dc}$. Substituting

$$\frac{E_{dc}}{\sqrt{2}} \text{ for } E_{ac},\ \frac{E_{dc}}{\sqrt{2}} I_{ac} = E_{dc}I_{dc} \quad \text{and}$$

145 $$I_{ac} = \sqrt{2}\ I_{dc} = 1.41\ I_{dc} \text{ amperes.}$$

Since the maximum value (I_m) of a sinusoidal alternating current equals $\sqrt{2}$ times the effective value the maximum value of the alternating current in a single-phase converter at unity power factor is given by $I_m = \sqrt{2} \cdot \sqrt{2}\ I_{dc} = 2\ I_{dc}$.

In a three-phase converter operating at unity power factor $\sqrt{3}\ E_{ac}I_{ac} = E_{dc}I_{dc}$ or

$$\sqrt{3}\sqrt{\frac{3}{8}}\ E_{dc}I_{ac} = E_{dc}I_{dc} \quad \text{and} \quad I_{ac} = \frac{1}{\sqrt{3}}\sqrt{\frac{8}{3}}\ I_{dc} \quad \text{or}$$

146 $$I_{ac} = \sqrt{\frac{8}{9}}\ I_{dc} = 0.943\ I_{dc} \text{ amperes.}$$

The general relation between I_{ac} and I_{dc} in any synchronous converter is given by

147 $$I_{ac} = \frac{2.83\ I_{dc}}{\eta n(\text{pf})} \text{ amperes}$$

where η is the efficiency, n is the number of slip rings (defined under 144), and pf is the power factor.

The Advantages of the Polyphase Converter. In a single-phase converter (Fig. 185) the direct current enters the armature at the negative brush and flows through two paths in the armature winding to the positive brush. The alternating current (for the position shown) enters the armature from the positive slip ring and flows through two paths in the armature winding to the negative slip ring. In conductor No. 1, the alternating emf

between the slip rings being zero for the position shown, the current will also be zero for operation at unity power factor and will vary during one revolution as shown in the curve (i_{ac}) in Fig. 186. The direct current flowing in conductor No. 1 will vary during one revolution as shown in curve (i_{dc}) in Fig. 186, i_{dc} being approximately equal to one-half the maximum value of i_{ac} and reversing in direction under each brush. The composite current (i_1) flowing in conductor No. 1 during one revolution is then given by the sum of i_{ac} and i_{dc} at any instant. In conductor No. 2 (located half-way between the slip ring connections) the composite current (i_2) is given at any instant by the sum of the currents i_{ac} and i_{dc} as shown in Fig. 187.

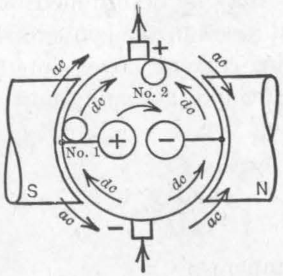


FIG. 185

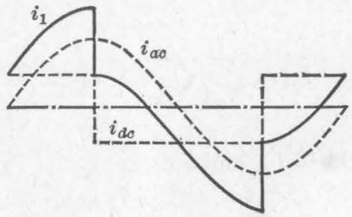


FIG. 186

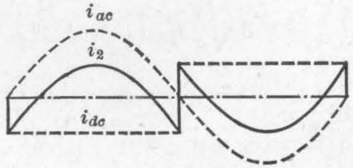
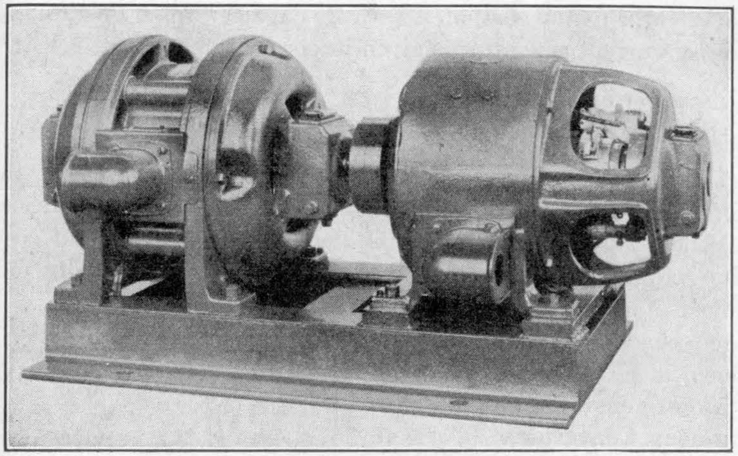


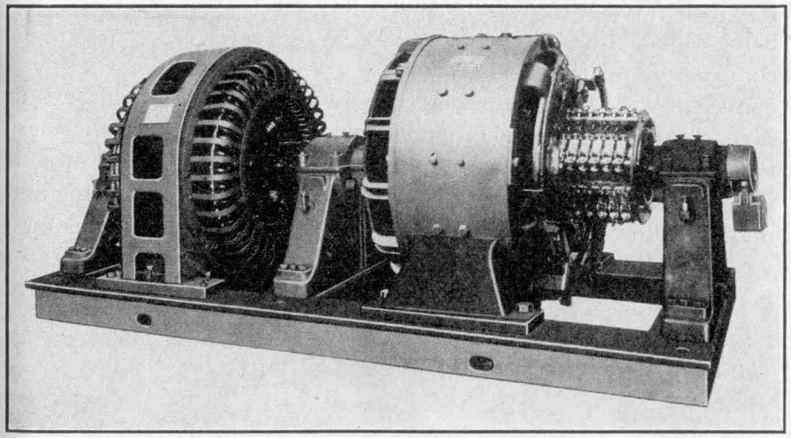
FIG. 187

Since the heating effect of the current is proportional to i^2R at any instant it will be noted by comparing i_1 and i_2 at any instant that more power will be converted into heat in conductor No. 1 than in conductor No. 2 (actually 6.6 times as much in No. 1 in one cycle as in No. 2). The capacity of a single-phase converter is thus limited by the excessive heating of those conductors located near the slip ring connections. A similar analysis of the heating effect in the various armature conductors of a polyphase converter will show that the relative heating effect becomes more uniform as the number of phases is increased. The average heating effect in the armature winding as a whole is also decreased because the average effective value of the composite current in a polyphase



Westinghouse Electric and Manufacturing Co.

Induction Motor-generator.



Westinghouse Electric and Manufacturing Co.

Synchronous Motor-generator.

converter operating at unity power factor is less than the direct current. The capacity of a synchronous converter operating at unity power factor compared with its capacity when operated as a direct-current generator is given in per cent as follows:

Number of slip rings	2	3	4	6	12
Relative capacity	85.2	133	162	193	219.5

The six-phase converter is used extensively for this reason, the increased capacity of the twelve-phase converter being insufficient in general to compensate for its increased complexity and cost. The six-phase diametrical transformer connections usually employed for the conversion of three-phase to six-phase are shown in Fig. 188.

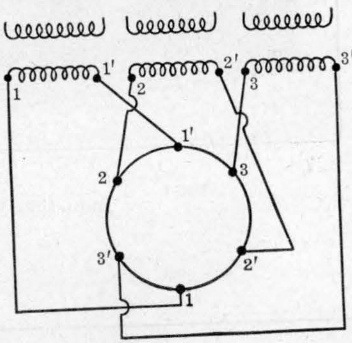


Fig. 188

Motor-generators versus Synchronous Converters. The conversion of alternating-current power to direct-current power or the reverse may also be accomplished by coupling an alternating-current motor to a direct-current generator, the combination being called a motor-generator. A comparison of the synchronous converter with the motor-generator reveals certain advantages in favor of the synchronous converter; namely, higher efficiency, lower cost, and less space requirement. The motor-generator, if it be an induction motor-generator, requires no synchronizing and may therefore be started more easily than the synchronous converter. The generated emf of the generator in a motor-generator may also be varied over a wider range than the generated emf of a synchronous converter.

Practice problems with answers for Chapter XII will be found on page 275.

CHAPTER XIII

ELECTRONIC THEORY AND APPLICATIONS

Thermionic Emission. Electrons may be drawn from a conducting material into the surrounding space by applying a potential gradient at the surface sufficient to overcome the forces which bind the electrons to the material. The required potential gradient in general is too high to give the method practical value. Bombardment of the surface with high-velocity particles will cause some degree of electronic emission but the strength and direction of the flow is not easily controlled and the surface will be quickly disintegrated if extraction of some magnitude is required.

Under conditions somewhat similar to the evaporation of molecules from liquids, electrons may leave heated materials with a comparatively low potential gradient at the surface or even with none at all. Tungsten is a good emitter at 2200 C, thoriated tungsten at 1800 C, and barium or cesium oxide at 800 C. Electronic devices operating at low potentials usually employ barium or cesium oxide coated filaments but at high potentials tungsten or thoriated tungsten filaments must be used to withstand the consequent forces of disintegration. The best source of emission when the current density is large is a pool of mercury with the liquid as a whole at a temperature ranging from 10 C (0.0005 millimeter Hg pressure) to 50 C (0.015 millimeter Hg).

Construction and Operation of the Diode. The simplest example of the use of thermionic emission is shown in the diode (Fig. 189). A heated filament (the cathode *C*) is centered in a hollow metal cylinder (the anode or plate *A*) and all are located in an evacuated glass or metal tube (*B*) with connecting pins (*DEF*) in the base. When the heating current is alternating the cathode is usually an indirectly heated thimble placed over the filament. A cross section of a diode without the evacuated enclosure is shown in Fig. 190.

With the diode in operation an electron carrying a charge (*e*)

and located at a distance (r) from the center of the filament will be acted upon by forces owing to the joint effect of the charges located at a distance greater than r and their equal and opposite charges located on the filament. Assuming r to be small compared

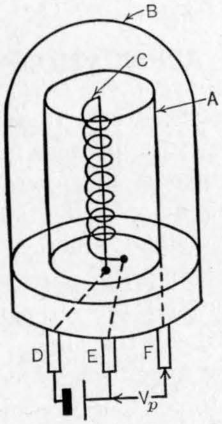


FIG. 189

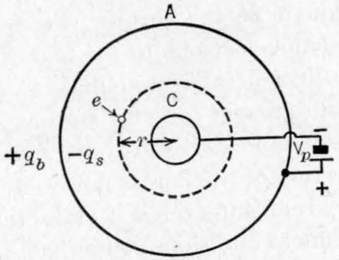


FIG. 190

with the axial length of the filament and taking the charge (q) per unit of axial length, the force will be given by $\frac{2\,qe}{r}$: outward for a positive outer charge, and inward for a negative outer charge. There will be no force due to any charge located between the filament and an imaginary cylinder of radius (r). With the battery connected as shown in Fig. 190 there will be two outer charges: $+q_b$ due to the battery and $-q_s$ (the space charge) due to the electrons moving from the filament to the plate. The resultant force on e will then be $\frac{2\,e}{r}(q_b - q_s)$.

With the temperature of the filament fixed, the plate current (I_p) for any plate potential (V_p) will be limited, as shown in Fig. 191 by (1) the rate of electron emission from the filament, and (2) by the space charge located in the outer space; that is, at a distance greater than r from the center of the filament. It will be noted that if the plate potential is alternating the force on any electron at a radius (r) will alternate from $\frac{2\,e}{r}(q_b - q_s)$ (outward) to

$\frac{2\,e}{r}(-q_b - q_s)$ (inward) and the device will serve as a half-wave rectifier of very small alternating currents.

The Function of the Grid in the Triode. If a cylindrical screen of widely spaced small wires (the control grid (CG) in Fig. 192) is located at a radius (r) from the center of the filament and the plate potential (V_p) is fixed, the plate current (I_p) will vary with the

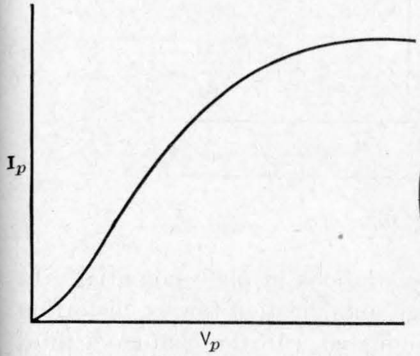


FIG. 191

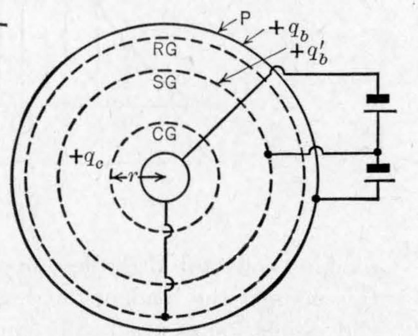


FIG. 192

grid potential (V_g) as shown in Fig. 193. The force on any electron between the grid and the filament will be $\frac{2\,e}{r}(q_b - q_s \pm q_c)$, where q_c is the charge on CG and depends upon the polarity of V_g. A grid potential of high frequency, for example, which alternates from A to B in Figs. 193 and 194 will cause the plate current to alternate unsymmetrically because the curve is not symmetrical about D. The plate current will vary as shown in Fig. 194 and the diaphragm of a telephone receiver connected in the plate circuit will move as shown by the dotted line. The same diaphragm would not move under the influence of the original high-frequency current because it possesses too much inertia. This illustrates the principle of the triode used as a detector. If the grid potential is adjusted so that it alternates between B and C (with less grid bias) on the straight part of the curve (Fig. 193) the plate current will alternate in exactly the same manner but with increased amplitude. This illustrates the principle of the triode used as an amplifier.

In the tetrode a second screen (the screen grid (*SG*) in Fig. 192) is placed between the control grid and the plate and is held at a fixed potential above the filament. Its consequent charge (q'_b)

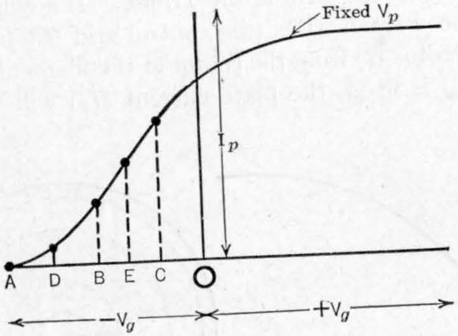


FIG. 193.

remains constant regardless of variations in plate potential. In this manner the tendency at high amplification toward distortion and oscillation is practically eliminated. In the pentode a third screen (the suppressor or repulsion grid (*RG*) in Fig. 192) is placed

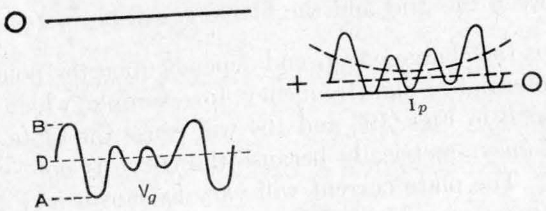


FIG. 194

between the screen grid and the plate, and is connected to the filament. This prevents a reverse flow of electrons due to secondary emission; that is, electrons emitted by the plate due to bombardment.

High Vacuum Tube Circuits. A simple form of radio detector circuit is shown in Fig. 195. The emf induced in the antenna (*A*) by the modulated oscillating current in the distant transmitter is transmitted through a transformer (*T*) to the grid (*G*). Tuning is

obtained by adjusting the variable condenser (*C*). The rectified (audible) current is converted into sound in the telephone receiver connected in the plate circuit or is sent on to other tubes for further amplification.

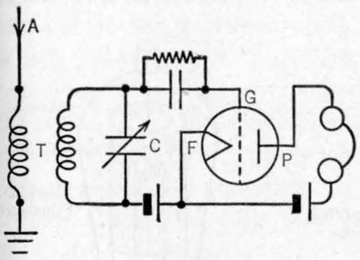


FIG. 195

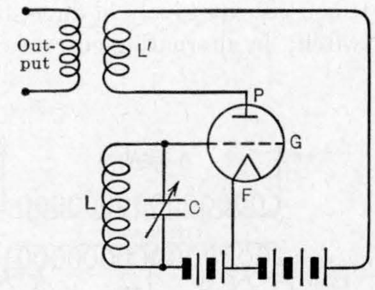


FIG. 196

An oscillator circuit for the production of high-frequency currents is shown in Fig. 196. Any slight inductive action causes a regenerative current to flow through L' in the plate circuit with consequent induction in L. The desired frequency, $f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$, is obtained by adjusting C. Many forms of oscillating circuits are used to produce the high-frequency currents (called carrier currents) flowing in broadcasting antennas and in multiplex telephone systems.

Effect of the Gas Content. If a thermionic tube is evacuated to a lesser degree — from 6 centimeters Hg to 76 centimeters (atmospheric pressure) — and a vapor, such as mercury, or a gas, such as argon, possessing molecules of large size is used, the plate current may be greatly increased by causing more collisions between the speeding electrons and the molecules in their path. The consequence of most of the collisions is to remove one or more of the orbital electrons from an associated atom so that the atom becomes positively charged (ionized). The electrons thus released augment the stream of electrons to the plate and collide with more molecules on the way. This ionization principle is employed in the " Tungar " and " Rectigon " rectifiers which operate with a plate current up to 5 amperes at potentials ranging from 6 to 220

volts. Full wave rectification is obtained by the use of two tubes connected as shown in Fig. 197.

The Grid-controlled Rectifier. A gas-filled triode (Fig. 198) with its heated cathode entirely surrounded by a cylindrical perforated grid is called a "Grid-Glow Tube" or a "Thyratron." It is used extensively in direct- or alternating-current circuits as a switch; in alternating-current circuits it also serves as a rectifier.

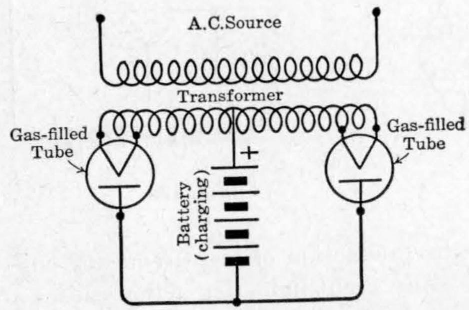


FIG. 197

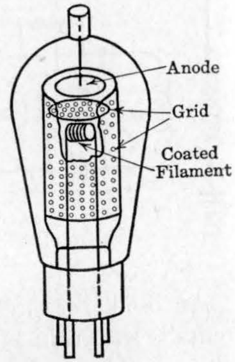


FIG. 198

No current will flow through the tube if the grid potential is made sufficiently negative to prevent electronic emission at the cathode. A reduction of the grid potential below the critical (cutoff) value will allow current to flow from anode to cathode. In alternating-current, grid-controlled tubes the arc may also be established by making the phase angle between the plate potential and a fixed cutoff grid potential more or less than 180 degrees. With a phase difference of 90 degrees, for example, the grid potential would be zero when the plate potential is a maximum and the arc would be established. After ionization is started the operation is not affected by restoring the original value or phase of the negative grid potential because positive ions attracted to the grid neutralize its negative potential. The current may be interrupted only by reducing the plate potential to a value insufficient to maintain the arc.

Though the highly evacuated triodes previously described may be used in communication systems for various types of accurate control, the gas-filled triode is used principally in power systems

for turning on and rectifying current. Since there are no moving parts it is best adapted to automatic apparatus requiring frequent starts or changes in speed. Grid-controlled rectifiers have a capacity as high as 100 amperes at low potentials. At current ratings up to 12.5 amperes the potential may be as high as 10,000 volts. Other applications of the grid-controlled rectifier which may assume increasing importance are in frequency changers and in inverters which convert direct-current power into alternating-current power at any desired frequency.

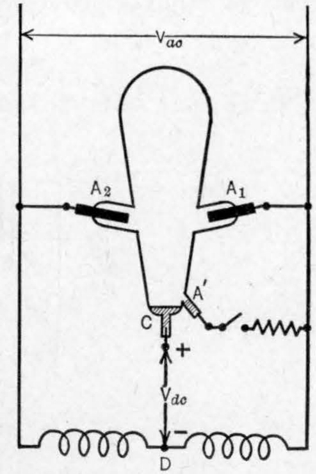


FIG. 199

The Glass Mercury Arc Rectifier. A highly evacuated glass chamber (Fig. 199) contains two recessed anodes (A_1A_2), a cathode (C), and an auxiliary anode (A'). The anodes (A_1A_2) are made of graphite or iron and the cathode (C) consists of a pool of mercury, a smaller pool of mercury also being located at the auxiliary anode (A'). The anodes (A_1A_2) are connected to the opposite alternating-current line wires and the auxiliary anode (A') is connected to one of the line wires through a resistance. The device in which direct current is to be established is connected between the cathode and the mid point (D) of a reactance connected between the line wires.

If the tube is tipped until the mercury in the auxiliary anode (A') flows into the pool of mercury at the cathode (C), an alternating current will flow from A' to C and establish an arc. This arc will rise quickly to the anodes (A_1A_2) but current will flow through this arc only from each anode to the cathode and not in the opposite direction. A direct current will then be established in any device connected between C and D. The direct potential between C and D will equal approximately one-half the average value of each half-cycle of the alternating potential (V_{ac}) minus the potential drop in the vacuum chamber, which is about 15 volts. The direct potential is then given approximately by

148 $$V_{dc} = \frac{\sqrt{2}\,V_{ac}}{\pi} - 15 = 0.45\,V_{ac} - 15 \text{ volts.}$$

The Steel-tank Mercury Arc Rectifier. The current capacity of the glass mercury arc rectifier is limited by the low mechanical strength and the low heat conductivity of the glass. The rectified current rarely exceeds 50 amperes at 230 volts. With smaller

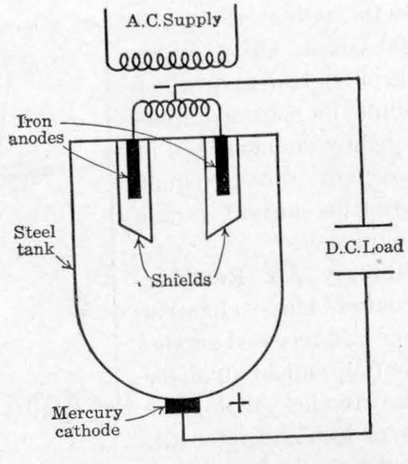


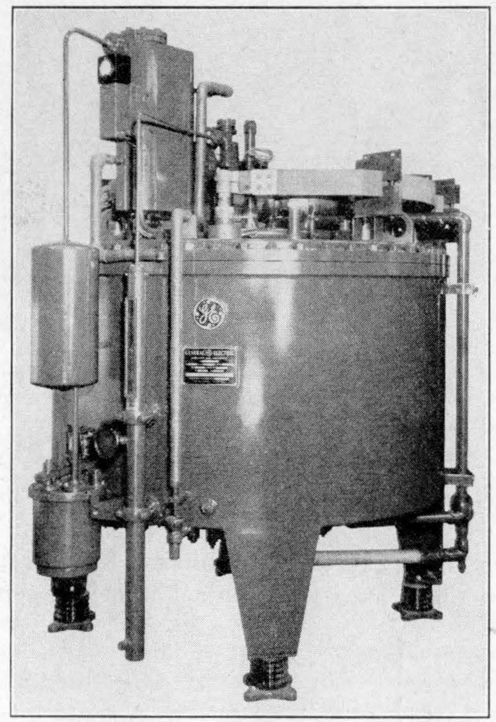
FIG. 200

currents the potential may be as high as 15,000 volts. Steel-tank rectifiers surrounded by circulating water have a much higher capacity and have replaced glass-tube rectifiers for heavy service. A typical form of construction of a steel-tank rectifier applied to a single-phase source is shown in Fig. 200. The usual number of phases is six, and occasionally twelve. Since inward leakage occurs at each electrode seal, vacuum pumps must be kept in continuous operation during the operation of the rectifier. Another pump keeps the water circulating through the water jackets and an outside radiator.

In the " Ignitron " mercury arc rectifier each anode is located in a separate, evacuated compartment which also contains an ignitor, a rod of high-resistance refractory material with a conical tip slightly immersed in the mercury pool and connected through an upper sealed electrode to the anode of a " Thyratron." When the anode in any compartment starts to become positive the " Thyratron " increases the potential between the ignitor and the mercury pool, ionizes the intervening vapor, and establishes an arc

between the anode and the mercury pool. With such accurate timing the tendency toward backfire in the rectifier is greatly reduced.

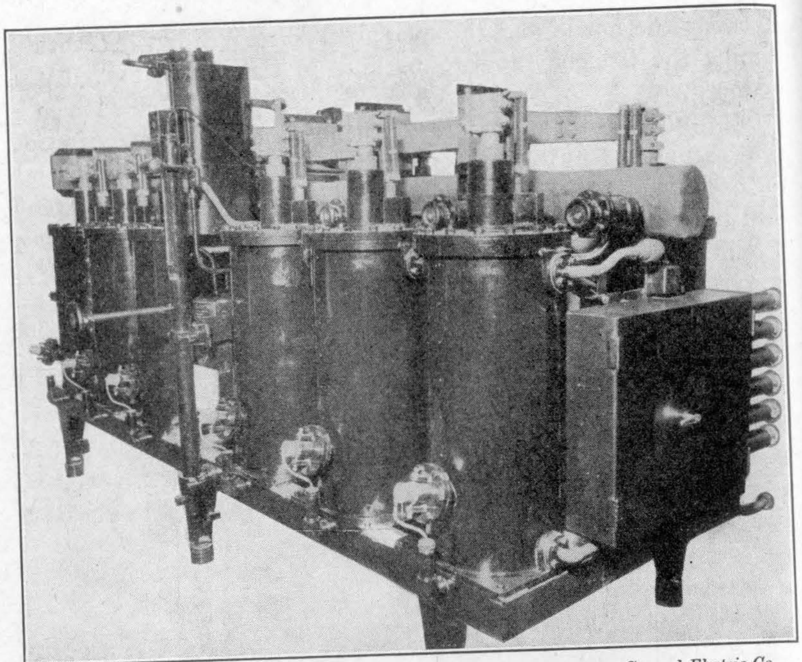
Steel-tank rectifiers are used principally in the conversion of alternating-current to direct-current power for electric railways and electrolytic plants. At 600 volts the efficiency is about 94 per cent and the power factor 96 per cent (both at full load and including



General Electric Co.

Six-phase, Multiple-electrode, Metal-tank Mercury Arc Rectifier.

the transformers). Rectifiers of this type are in commercial operation with a current capacity of 5000 amperes at 625 volts. For periods of one minute the capacity may be as high as 15,000 amperes. The steel-tank rectifier surpasses the synchronous converter in (1) quicker starting, (2) higher efficiency, (3) less space,



General Electric Co.

Six-phase, Single-electrode, Metal-tank, Ignitron-type Mercury Arc Rectifier.

(4) lighter weight, (5) less maintenance cost, and (6) higher short-time overload.

The Copper Oxide and the " Selenium " Rectifiers. Two dissimilar conducting materials in contact will, in general, conduct

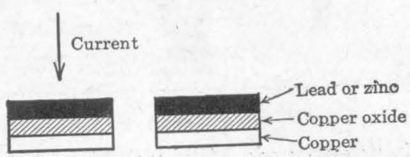
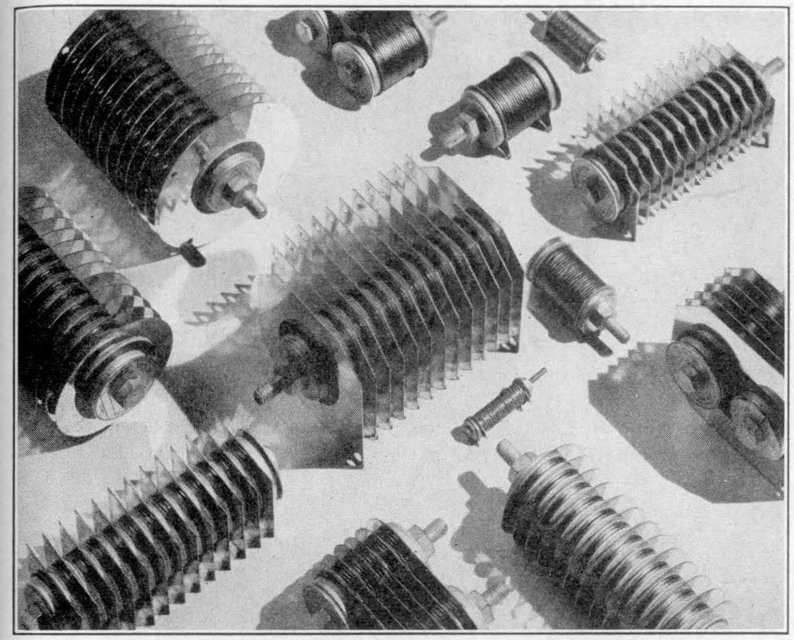


FIG. 201

better in one direction than in the other. If a copper washer is oxidized on one side at a temperature near its melting point, current will flow through the film of copper oxide to the washer, but very little current will flow the other way. This indicates

that electrons flow with difficulty through the copper oxide into the washer but pass through the oxide easily in the opposite direction. A common form of copper oxide rectifier, called the " Rectox," is shown in Fig. 201. A satisfactory contact of the circuit

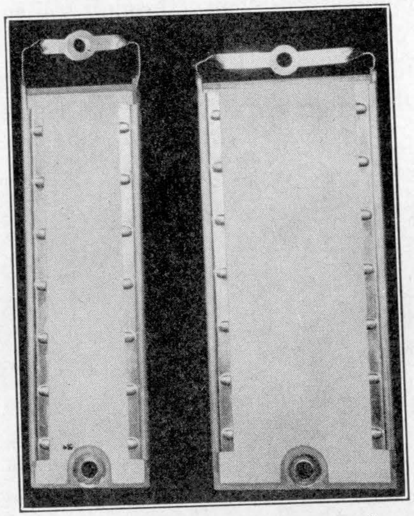


Westinghouse Electric and Manufacturing Co.

Various Types and Sizes of " Rectox " Rectifiers.

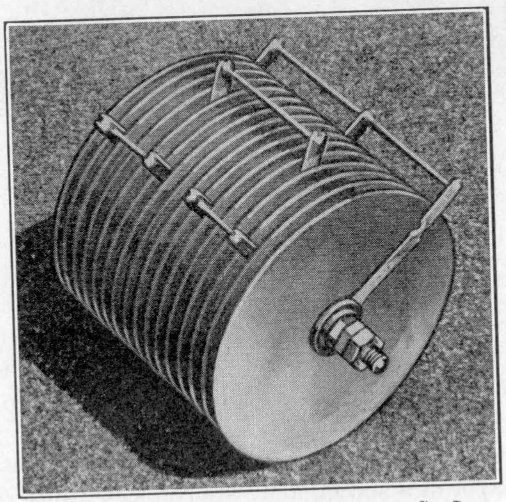
with the copper oxide is obtained by pressing a soft metal such as lead or zinc against the oxide, or by some form of adherent plating. These units may be piled up consecutively in series and held tightly together by insulated through bolts or bolted together separately for parallel connection. By these connections rectification may be obtained of a current of 0.1 ampere at 80,000 volts or 1200 amperes at 12 volts.

In the " Selenium " rectifier, iron discs coated with selenium and a thin layer of a special alloy are connected in series, parallel or bridge formation and operate in the same manner as the copper oxide rectifier.



Westinghouse Electric and Manufacturing Co.

Two Sizes of " Rectox " Rectifier Plates with a Collecting Surface of Non-corroding Alloy Sprayed on the Graphitized Cuprous Oxide.



International Telephone Development Co., Inc.

Selenium Rectifier.

Gas- and Vapor-filled Lamps. Energy is required to move an electron from a lower to a higher quantum level in an atom (then called an excited or metastable atom), or to remove it entirely from an atom (then called an ionized atom). In either atom the normal state is restored almost immediately by the return of the original electron, or another one, to the original quantum level. The return to normality is accompanied by radiation of energy at various frequencies depending upon the nature of the gas.

Cylindrical tubes having cold or heated electrodes at the ends and containing gases, such as neon, helium, or argon (the last in mixtures only), or vapors, such as mercury or sodium, are used effectively as sources of light. Their efficiencies depend upon the relative proportion of the radiation which falls in the visible spectrum. The characteristic colors and efficiencies in lumens per watt vary as follows: sodium (yellow, 50–100); high pressure mercury (blue green, 30–35); neon (orange red, 15–40); low pressure mercury (blue green, 15–20); helium (yellow white, 4–10). Light blue is obtained by combining mercury, argon, and neon; light green with the same combination in a yellow tube, etc. The ionization of sodium is accomplished only by combining liquid sodium with neon gas and maintaining the tube at high temperature by placing the tube in a vacuum chamber.

High potential is required to maintain the arc in gaseous tubes having cold electrodes: from 2000 to 15,000 volts in tubes ranging from 1 to 70 feet in length. All tubes must have some type of impedance (ballast) connected in series with them because the resistance of the arc decreases with an increase of current. Mercury vapor tubes containing an inner coating of a fluorescent material on the glass, such as cadmium tungstate or zinc sulphide, and called fluorescent lamps, convert a large part of their invisible ultraviolet radiation into visible radiation of practically any desired color.

Photoelectric Emission. Some metals, notably sodium, potassium, cesium, and barium, emit electrons at room temperature when illuminated by radiation of the proper frequency. The kinetic energy of each emitted electron is directly proportional to the frequency of the impinging radiation above a certain critical (threshold) value for each metal. The number of electrons emitted per second depends upon the intensity of the radiation.

A photoelectric cell connected as shown in Fig. 202, where R represents a resistance of several megohms, will operate a relay through an amplifier every time light is removed from the cathode. When light shines on the light sensitive cathode the cell becomes conducting and the C battery makes the grid (G) sufficiently negative to make the plate current zero as shown in Fig. 193. Removal of the light causes the grid to assume about the same potential as the filament (F). The B battery will then send a

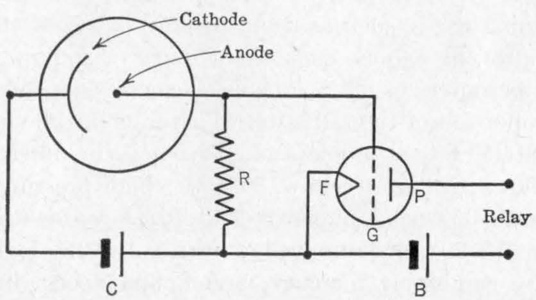


FIG. 202

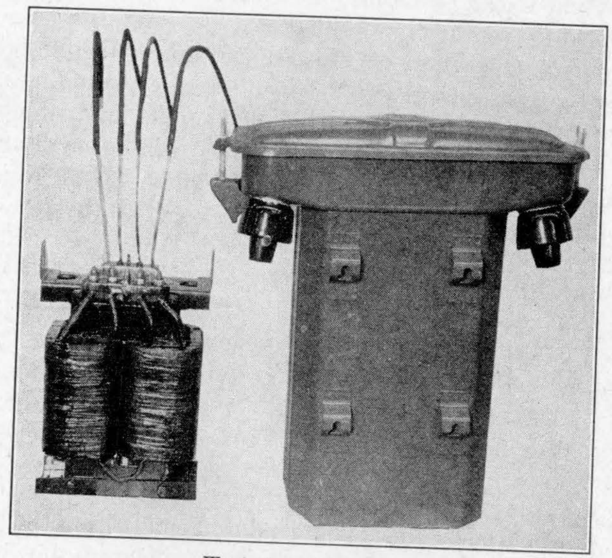
current through a relay which may count boxes moving on a conveyor belt, switch on a door-opening mechanism, or reject packages issuing from an automatic machine when they are not properly wrapped with tin foil, etc.

Certain coatings, such as iron selenide on iron or copper oxide on copper, possess a photovoltaic effect in which the impinging radiation will generate an emf between the metal backing and an outer metallic ring on the front of the coating. In this manner the energy of the radiation may be converted with low efficiency into electric energy. A photovoltaic cell connected in series with a microammeter, for example, may be used to measure the illumination in a building.

CHAPTER XIV

THE TRANSFORMER

Construction. A transformer consists of two coils of wire wound upon a magnetic core made of soft iron laminations. In the "Spirakore" transformer two long strips of soft iron are wound spirally and compactly about the windings. In another form of construction a long, single lamination of variable width is wound



Westinghouse Electric and Manufacturing Co.

Rectangular Core-type Transformer.

on a rectangular frame to produce a laminated core of circular cross section perpendicular to the laminations. The two windings are then wound together on split reels placed on each straight leg of the laminated core. The core with its two windings is usually placed in a steel case filled with insulating oil, the oil also serving to conduct heat away from the windings and core by convection. To

reduce the fire hazard many transformers are now filled with a fireproof insulating liquid. The two windings, while insulated from each other, are intermingled so that their mutual inductance will be a maximum. The object of the transformer is to transform alternating-current power at one potential into alternating-current power at another potential. The winding which receives electric power from the source is called the primary winding and the winding which delivers electric power to the load is called the secondary winding.

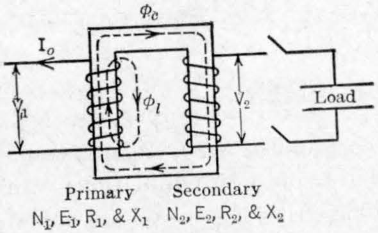


FIG. 203

Principle of Operation of the Transformer. If the primary winding of a transformer with an open secondary winding is connected to an alternating-current line of V_1 volts line potential, as shown in Fig. 203, the primary current (I_0) will be small and will lag the terminal potential (V_1) nearly 90 degrees. If the resistance of the primary winding were zero and the core loss (hysteresis and eddy-current losses in the iron core) were zero the terminal potential (V_1), primary current (I_0) and induced emf (E_1') in the primary winding would be represented by the vector diagram shown in Fig. 204. Here the primary current actually lags the terminal potential by 90 degrees and is of low magnitude $\left(I_0 = \dfrac{V_1}{L\omega}\right)$. If the resistance of the winding and the core loss are considered, the primary current will be sensibly of the same order of magnitude but will lag the terminal potential less than 90 degrees as shown in Fig. 205.

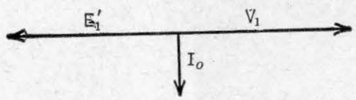


FIG. 204

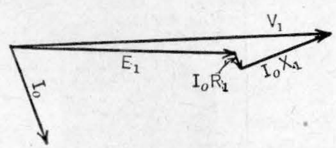


FIG. 205

The alternating magnetic flux which induces the emf (E_1') in Fig. 204 may be resolved into two components (Fig. 203): the

leakage flux (ϕ_l) which circulates through part of the core and the surrounding air, and the core flux (ϕ_c) which circulates through the core only and therefore links both the primary and secondary windings. If the leakage-inductance (L_1) of the primary winding is determined by $\dfrac{N_1\phi_l}{i_0 \times 10^8}$ the reactance potential in the primary winding will be given by $I_0\, 2\, \pi f L_1$ or $I_0 X_1$. The impressed primary potential (V_1) at no load must then equal the vector sum of the constituent potentials, I_0R_1, I_0X_1, and E_1, as shown in Fig. 205 where E_1 equals the effective value of $\dfrac{N_1}{10^8}\dfrac{d\phi_c}{dt}$. It should be noted that E_1 in Fig. 205 is that part of V_1 which must be supplied to neutralize the induced back emf, E_1' in Fig. 204.

Since the alternating core flux links both primary and secondary windings the emf induced in each winding per turn will be the same. The ratio of the primary emf to the secondary emf will then be given by

149 $$\frac{E_1}{E_2} = \frac{N_1}{N_2} = T_1,$$

where T_1, the ratio of the number of primary to secondary turns, is called the ratio of transformation (primary to secondary).

If a load is now connected to the secondary winding the secondary current will weaken the core flux (ϕ_c), reduce the primary emf (E_1) and increase the primary current. Equilibrium will be established when the primary no load current (I_0) is augmented by an additional primary current (I_1') of such magnitude that $N_1I_1' = N_2I_2$. The demagnetizing effect of the secondary ampere turns (N_2I_2) will then be counterbalanced by the magnetizing effect of a component of the primary ampere turns (N_1I_1'). The complete vector diagram of the loaded transformer is then represented by Fig. 206. The primary current (I_1), the vector sum of I_0 and I_1', is only slightly greater than I_1'. Then $N_2I_2 = N_1I_1$ (approximately) and

150 $$\frac{I_1}{I_2} = \frac{N_2}{N_1} = \frac{1}{T_1} \text{ (approximately).}$$

The secondary terminal potential (V_2) equals the secondary emf (E_2) minus (vectorially) the secondary reactance potential

(I_2X_2) due to the alternating secondary leakage flux, and the secondary resistance potential (I_2R_2). The power factor of the transformer at the primary terminals equals $\cos\theta_1$ and the power factor of the secondary load equals $\cos\theta_2$.

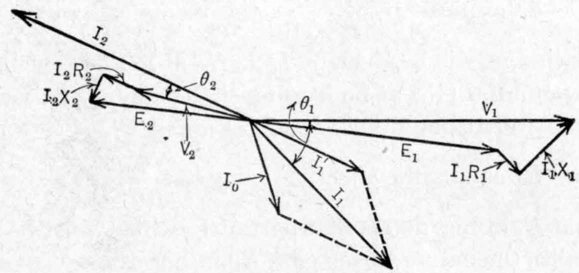


FIG. 206

Transformer Calculations. The relationship of the primary and secondary terminal potentials of a loaded transformer may be obtained from Fig. 206 but the calculation may be simplified by substituting composite or equivalent values of resistance and reactance for the individual resistances and reactances of the two windings. The composite resistance and composite reactance of a transformer may be determined experimentally as follows. The power input (P_1) and the primary current (I_1) of a transformer with the secondary short-circuited is measured as shown in Fig. 207 with the primary potential (V_1) reduced to such a magnitude (about 5 per cent of normal) that the primary current (I_1) does not exceed the normal rating of the primary winding. Since the core loss (the hysteresis and eddy-current losses) of a transformer operating under reduced primary potential is small the power input (P_1) equals the copper losses (approximately) in the two windings. The composite resistance (R_{c1}) of the transformer from the primary side is then given by

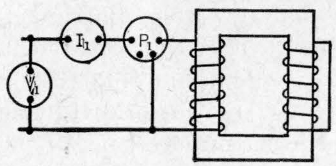


FIG. 207

151 $$R_{c1} = \frac{P_1}{I_1^2} \text{ ohms.}$$

The composite impedance (Z_{c1}) of the transformer from the primary side is given by

152 $$Z_{c1} = \frac{V_1}{I_1} \text{ ohms}$$

and the composite reactance (X_{c1}) of the transformer from the primary side is given by

153 $$X_{c1} = \sqrt{(Z_{c1})^2 - (R_{c1})^2} \text{ ohms.}$$

Since $I_1^2R_{c1} = I_2^2R_{c2}$ where R_{c2} is the composite resistance of the transformer from the secondary side and since $I_1^2 = \frac{I_2^2}{T_1^2}$ (approximately), then

154 $$R_{c2} = \frac{R_{c1}}{T_1^2} \text{ ohms.}$$

The composite reactance of the transformer from the secondary side is given by

155 $$X_{c2} = \frac{X_{c1}}{T_1^2} \text{ ohms.}$$

An equivalent transformer may then be substituted for the actual transformer as shown in Fig. 208. The equivalent transformer possesses no primary resistance or reactance, the secondary resist-

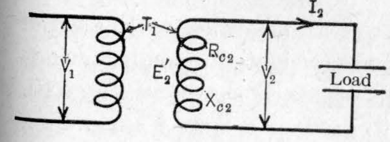


FIG. 208

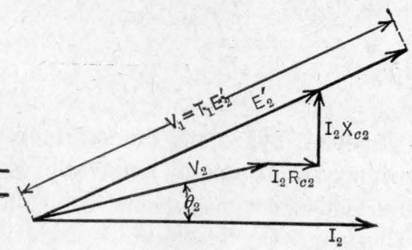


FIG. 209

ance is R_{c2} and the secondary reactance is X_{c2}. The vector diagram for this equivalent transformer is shown in Fig. 209. Then for any value of V_2, I_2 and θ_2 ($\sin\theta_2$ is + for a lagging

current and − for a leading current), V_1 is given by

$$156 \quad V_1 = T_1\sqrt{(V_2 \cos \theta_2 + I_2R_{c2})^2 + (V_2 \sin \theta_2 + I_2X_{c2})^2} \text{ volts.}$$

The voltage regulation (VR) of a transformer at any load is determined by

$$157 \quad \text{VR} = \frac{\frac{V_1}{T_1} - V_2}{V_2} 100 \text{ per cent}$$

where V_1 (assumed constant) is the primary terminal potential, V_2 (computed from 156) is the secondary terminal potential under the stated load conditions, and T_1 is the ratio of transformation (primary to secondary). It will be noted that the voltage regulation at any load is the percentage rise of potential on the secondary side when the stated load is removed. In transformers applied to lighting circuits the voltage regulation should not exceed 3 or 4 per cent because a reduction of load from full load to a light load might otherwise cause a rise of potential sufficient to burn out the remaining lamps.

If the power input to a transformer is measured as shown in Fig. 207 but at rated primary potential with the secondary open-circuited the core loss will be given approximately by P_1 since the copper loss at no load is small compared with the core loss. The core loss (P_c) may thus be determined experimentally and the efficiency of the transformer under any condition of secondary load is given by

$$158 \quad \eta = \frac{V_2I_2 \cos \theta_2}{V_2I_2 \cos \theta_2 + I_2{}^2R_{c2} + P_c}.$$

Special Types of Transformer. A transformer with a fixed primary winding and a movable counterweighted secondary winding, called a constant-current transformer, is shown in Fig. 210. The magnetic circuit is designed to produce a large leakage flux. When the secondary current is zero the secondary winding rests upon the primary winding and is linked by most of the flux produced by the primary current. If a load is connected to the secondary winding a force of repulsion between the primary and secondary currents causes the secondary winding to rise. The

linkage flux and secondary emf are then reduced in consequence and the secondary current will not increase as much as it would if the secondary winding were fixed with respect to the primary winding. A change in the resistance of the secondary circuit is thus accompanied by a corresponding change in the secondary emf due to a change in the position of the secondary winding. The secondary current will then remain sensibly constant for a moderate change in the secondary resistance. Constant-current transformers are used extensively in connection with series street lighting systems.

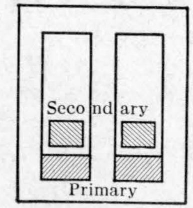


FIG. 210

A transformer in which part of the primary winding serves as the secondary winding (or the reverse), called an auto-transformer, is shown in Fig. 211. The principal advantage of this type of transformer is in the saving of a part of the weight of copper wire

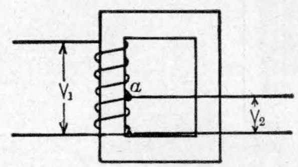


FIG. 211

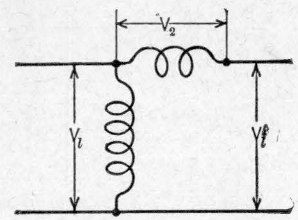
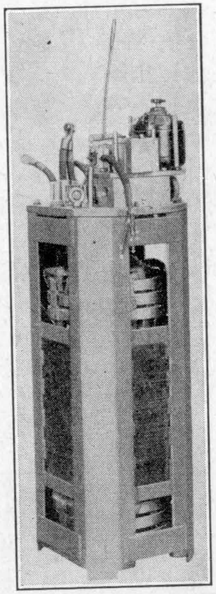


FIG. 212

required in the ordinary transformer. It actually saves that part of the primary winding which the secondary replaces. If an adjustable contact is provided at a the secondary potential (V_2) may be varied from zero to V_1. This arrangement is frequently used in a device called a compensator employed in starting induction motors. The induction regulator used for the adjustment of line potential in transmission lines consists of an auto-transformer connected as shown in Fig. 212. The secondary winding in this case is mounted upon a shaft so that the secondary winding may be turned with respect to a fixed primary winding. The linkage flux may then be varied from zero to a maximum and the line potential (V_l') may be changed gradually from V_l to $V_l \pm V_2$. In the three-phase induction regulator the potential (V_2) between the ter-

minals of each of the three rotor windings is practically constant. In this case the turning of the rotor changes the phase relation between V_l and V_2 and thereby changes V_l'.



General Electric Co.

Single-phase Induction Regulator.

Transformer Connections in Three-phase Circuits. A three-phase transformer may be constructed, as shown in Fig. 213, for example, containing three primary windings and three secondary windings connected respectively in Y or Δ. The cost of such a transformer is less than that of three single-phase transformers serving the same purpose and it has a higher efficiency. Single-phase transformers connected in Y or Δ are used more extensively than three-phase transformers, however, because single-phase reserve units are less expensive, high temperature in one single-phase transformer will not injure the other transformers and any

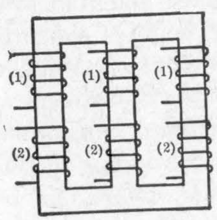
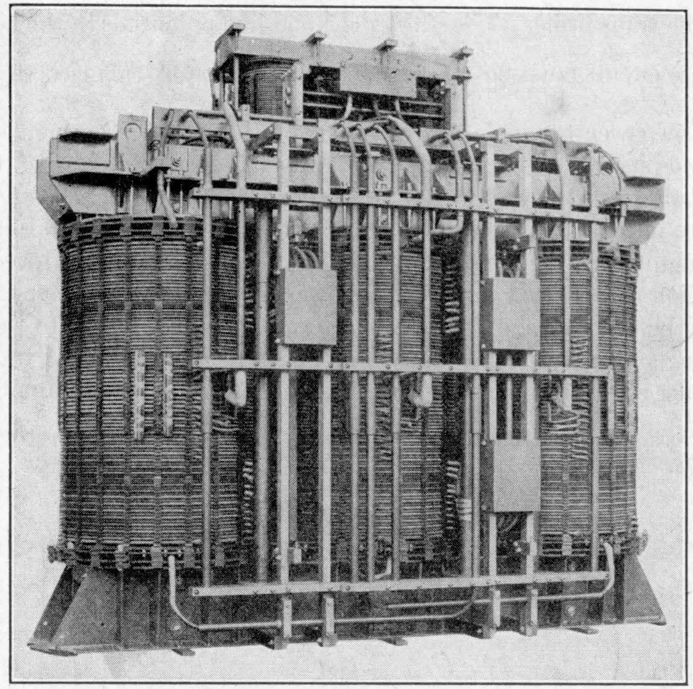


FIG. 213



General Electric Co.

Three-phase Transformer.

single-phase transformer may be repaired while the other transformers remain in service. When two sets of transformers are connected in parallel to the primary and secondary circuits of a three-phase system any combination of Δ or Y connection may be employed in each set except that with one set of transformers connected ΔY or YΔ the other set may not be connected ΔΔ or YY.

In the Scott connection two transformers connected as shown in Fig. 214 will convert three-phase to two-phase power, or the reverse. If the ratio of transformation (primary to secondary) in the transformer $cd - gh$ is T_1, then the ratio of transformation

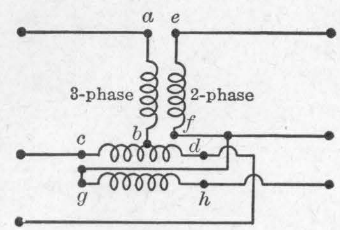


FIG. 214

in the transformer $ab - ef$ to give equal line potentials in the two-phase circuit must be $\frac{2}{\sqrt{3}} T_1$. Transformation of balanced three-phase power to single-phase power, or the reverse, through one single-phase transformer is impossible because the sum of the instantaneous powers in the respective three phases of a balanced three-phase system is constant while the instantaneous power in a single-phase system, as shown on page 108, is variable. The conversion of balanced three-phase power to single-phase power may only be accomplished by dividing the single-phase load into three equal and separate loads each supplied by a single-phase transformer connected to one of the phases of the three-phase circuit.

Practice problems with answers for Chapter XIV will be found on pages 276 to 278.

CHAPTER XV

THE THREE-PHASE INDUCTION MOTOR

The Production of a Rotating Magnetic Flux. The magnetic flux traversing the space between the two rotating magnetic poles, shown in Fig. 215, may be represented by a vector of constant length rotating at the same speed as the rotating poles. If the

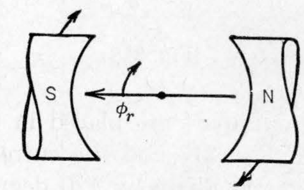


FIG. 215

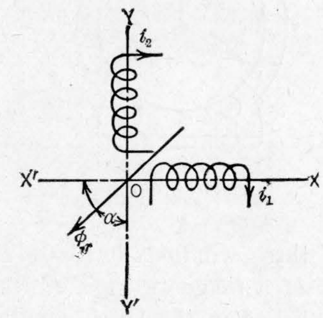


FIG. 216

axes of two stationary coils of wire are displaced by 90 degrees and the sinusoidal currents (i_1 and i_2) established in the two coils differ in phase by 90 degrees the magnetic flux along the axis XX' in Fig. 216 may be represented by $\phi_{xx'} = \Phi_m \sin \omega t$ and along the axis YY' by $\phi_{yy'} = \Phi_m \sin(\omega t + 90°) = \Phi_m \cos \omega t$, the maximum flux produced by each coil being assumed the same. The resultant magnetic flux (ϕ_r) through O, the intersection of the two axes, at any instant is then given by

$$\phi_r = \sqrt{(\Phi_m \sin \omega t)^2 + (\Phi_m \cos \omega t)^2}$$
$$= \Phi_m \sqrt{\sin^2 \omega t + \cos^2 \omega t} = \Phi_m.$$

The angle (α) between the direction of the flux and the YY' axis at any instant is given by $\alpha = \tan^{-1} \frac{\sin \omega t}{\cos \omega t} = \tan^{-1} \tan \omega t = \omega t.$

The magnetic flux through O will then be of constant magnitude (Φ_m) and will rotate at a constant angular velocity (ω). It will be noted that a rotating magnetic flux similar to that shown in Fig. 215 may be produced by two or more stationary coils of wire conducting sinusoidal currents of equal magnitude and frequency differing in phase respectively by the angle of displacement between the axes of the coils.

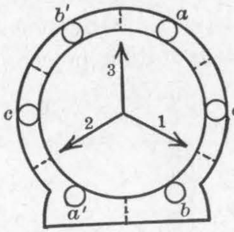


FIG. 217

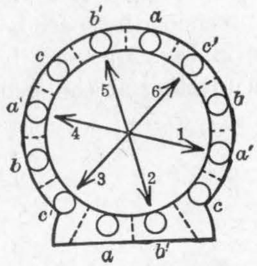
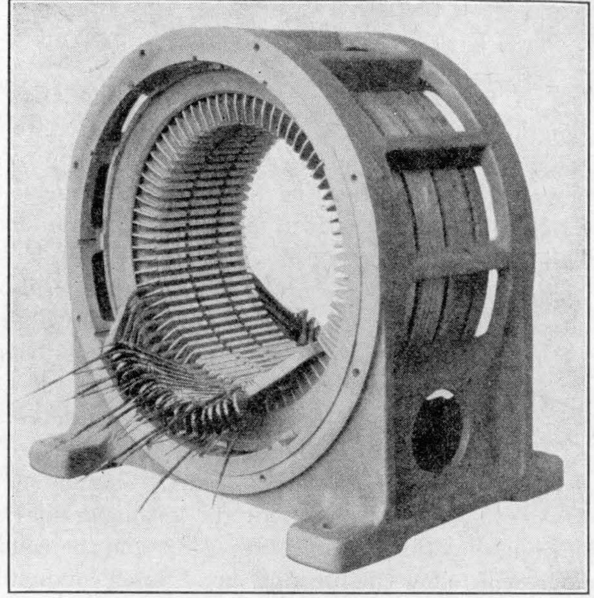


FIG. 218

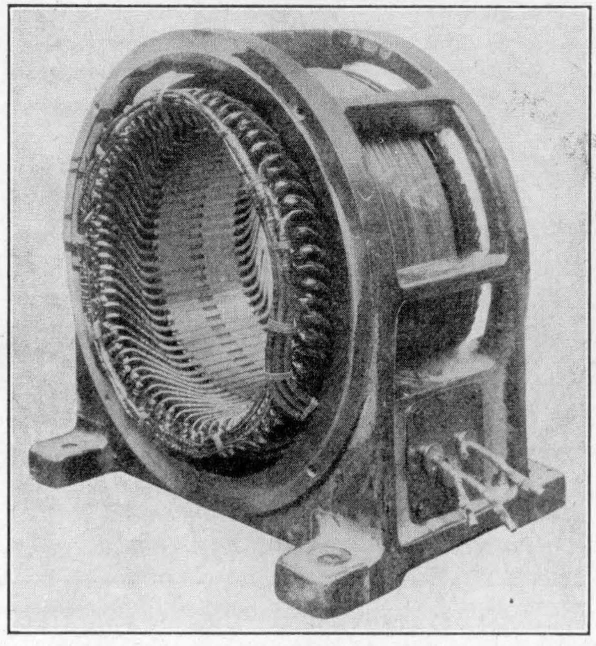
If three windings located 120 degrees apart are placed in the slots of a magnetic core as shown in Fig. 217 and the currents established in the three windings differ in phase by 120 degrees a rotating flux of constant magnitude and constant angular velocity will be produced. When the current in the phase aa' is a positive maximum the position of the rotating flux is represented by vector (1) and by vectors (2) and (3) when the currents in phases bb' and cc' respectively are a positive maximum. In Fig. 217 there is one complete set of three-phase windings and the rotating flux makes one revolution in the cyclical period (T seconds) of the three-phase currents. When there are two sets of three-phase windings as shown in Fig. 218 the rotating flux moves from the position of vector (1) to vector (4), for example, during a cyclical period and makes a complete revolution in 2 T seconds. The angular velocity (S_f) of the rotating flux then depends upon the frequency (f) of the three-phase currents and the number of phase sets (m), and is given by

$$S_f = \frac{60\,f}{m} \text{ revolutions per minute.}$$



General Electric Co.

Partially-wound Stator of a Three-phase Induction Motor.



General Electric Co.

Stator of a Three-phase Induction Motor.

Principle of Operation of the Three-phase Induction Motor. If three windings are placed in the slots of a laminated iron core as shown in Figs. 217 or 218 and are connected in Y or Δ to a three-phase source of power a rotating flux of angular velocity (S_f), given by 159, will be produced within the space surrounded by the three windings. The direction of the emf generated in any conductor located within this space (by the right-hand rule) will be downward at the instant shown in Fig. 219 and the direction of the current established in the conductor by the generated emf when the ends of the conductor are connected will also be downward. The electromagnetic force (F) acting on such a conductor (by the left-hand rule) will then be in the same direction as the rotating flux and the conductor, if free to move, will follow the rotating flux. Each conductor on the

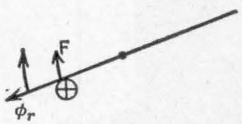
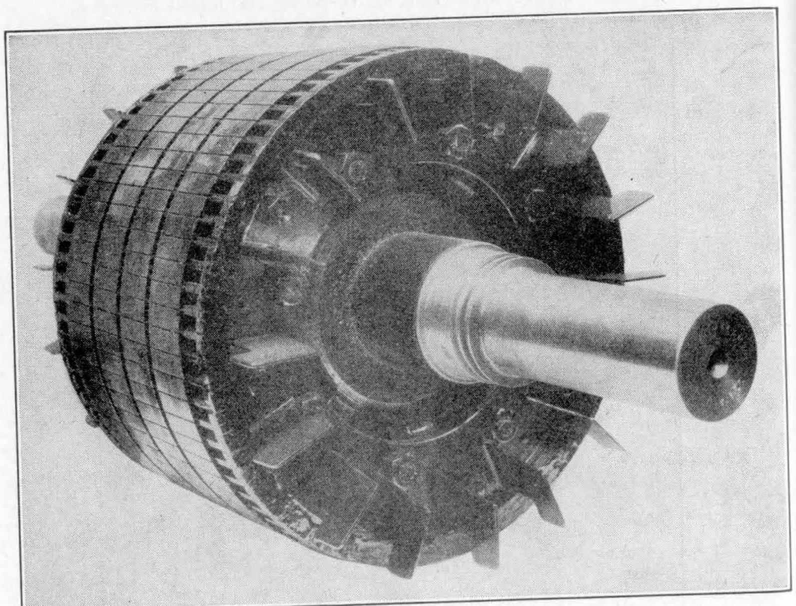


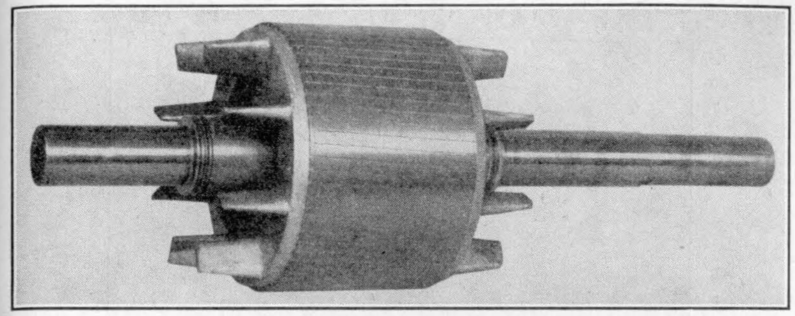
FIG. 219



General Electric Co.

Brazed Bar-wound or Squirrel-cage Rotor of a Three-phase Induction Motor.

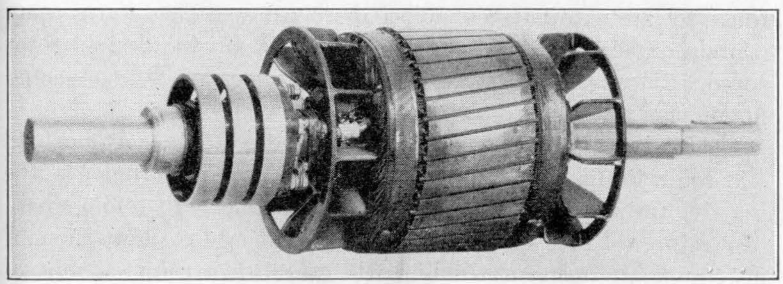
rotating member of a three-phase induction motor is thus acted upon by a force which causes the rotating member to turn in the same direction as the rotating flux.



General Electric Co.

Three-phase Induction Motor Rotor with Cast Aluminum Squirrel-cage Winding.

Construction of the Three-phase Induction Motor. The primary structure, called the stator, contains a three-phase Y- or Δ-connected winding embedded in the slots of a laminated iron core and is similar to the stationary armature of a three-phase synchronous generator. The secondary structure, called the rotor,

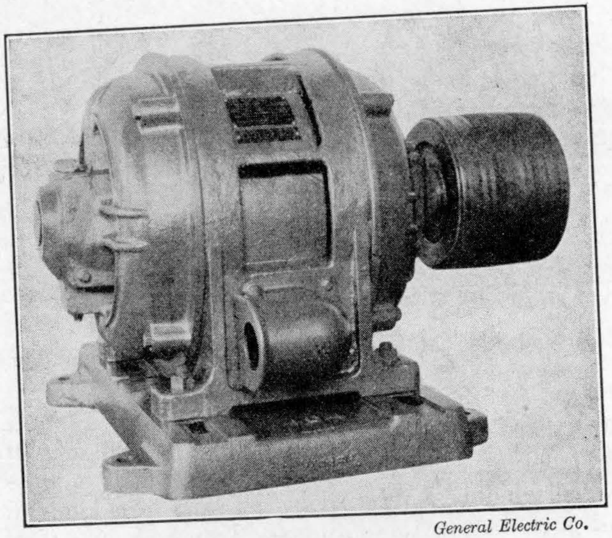


General Electric Co.

Wound Rotor for Three-phase Induction Motor.

contains either a bar or a wire winding embedded in the slots of a laminated iron core which is keyed to the shaft or a spider attached to the shaft. In the bar winding or squirrel-cage rotor, copper bars embedded in the slots are connected at each end of the rotor by

copper rings. In the wire wound or slip-ring rotor, three groups of insulated copper wires are embedded in the rotor slots and are Y connected. The terminals of the three windings of the wound rotor are either short-circuited or connected through three slip



General Electric Co.

Three-phase Induction Motor.

rings to an external Y-connected rheostat. The stator may contain one or more phase sets depending upon the desired rotor speed. It will be noted that the rotor windings are not connected in any way to the three-phase source of power.

Relation between Load and Speed of the Rotor. At no load the rotor torque must only be sufficient to counterbalance the reactive torque due to the rotational losses and is therefore small. The rotor will then turn at such a speed at no load that the emf generated in the rotor winding will establish a rotor current of sufficient magnitude to produce the required no load torque. Since the generated emf in the rotor depends upon the relative speed of the rotor and the rotating flux and the emf required at no load is small the rotor speed at no load will nearly equal the flux speed. It will be noted that the rotor speed cannot actually equal the flux speed at any time since there would then be no relative motion and the rotor emf would be zero.

An increase of load (or reactive torque) will cause the rotor to slow down until the increased rotor emf establishes sufficient current to produce the required electromagnetic torque. The speed of an induction motor is usually indicated by the ratio of the difference between the flux speed (S_f) and the rotor speed (S_r), and the flux speed (S_f). This ratio, called the slip (s) and expressed in per cent, is given by

160 $$s = \left(1 - \frac{S_r}{S_f}\right) 100 \text{ per cent.}$$

At no load the slip is a fraction of a per cent and at full load the slip ranges from 5 to 15 per cent, decreasing as the rating of the motor increases. In very large motors the slip is sometimes less than 5 per cent at full load. The slip is usually measured by some stroboscopic method. In one form, a disc with alternate white and black sectors is attached to one end of the shaft and is illuminated by a small neon or mercury-vapor tube connected between two of the stator terminals. Since such lamps flash twice per cycle a disc with 4 m black and white sectors (m is the number of phase sets on the stator) will appear to stand still if the rotor is turning at synchronous speed and will appear to turn slowly with a speed $S_f - S_r$, when not running in synchronism.

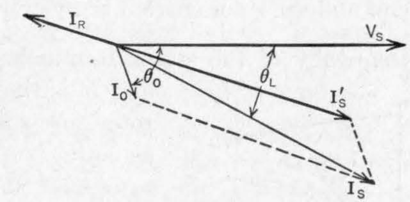


Fig. 220

Effect of Load on Power Factor. At no load the stator current must be of sufficient magnitude to produce the rotating flux and provide the power absorbed by the no load losses. The no load stator current (I_0 in Fig. 220) in its magnetizing action resembles the no load primary current of a transformer in that it lags the terminal potential to a considerable degree but differs in respect to magnitude, the ratio of no load stator current to full load stator current in the induction motor being much greater than in the transformer. This is due to the high reluctance of the air gaps traversed by the rotating flux in the motor. To reduce this reluctance and incidentally the no load stator current, induction motors are usually constructed with a very small clearance between

the rotor and the stator, often only a few hundredths of an inch.

The induction motor for the reasons stated operates at no load with a comparatively large stator current and at a very low power factor ($\cos \theta_0$ in Fig. 220). The rotor mmf in an induction motor, corresponding to the armature reaction in the machines discussed previously, is demagnetizing and its effect is similar to that of the secondary ampere turns of a transformer. An increase in load therefore weakens the rotating flux, reduces the stator emf generated by the rotating flux and increases the stator current. Since the component (I_s') of the stator current which balances the demagnetizing rotor current (I_r) is nearly in phase with the stator potential (V_s) an increase in load is accompanied by an increase in power factor. The improvement in power factor with an increase in load is restricted, however, by the abnormal magnitude of the stator magnetizing current (I_0) and the power factor ($\cos \theta_2$) at full load is seldom greater than 90 per cent. The typical operating characteristics of a three-phase induction motor are shown in Fig. 221.

Starting Conditions in the Three-phase Induction Motor. With the rotor at rest the induction motor resembles a short-circuited transformer. The phase angle (θ) between the rotor emf and the rotor current is given by $\tan \theta = \dfrac{2\,\pi f s L}{R}$, where f is the frequency of the stator terminal potential, L is the inductance, and R is the resistance of each path in the rotor, and s is the slip of the rotor, expressed as a decimal. The frequency (f) of the rotor emf at standstill (100 per cent slip) equals the frequency of the stator terminal potential and since the resistance of the rotor (R) is small compared with the rotor reactance ($2\,\pi f s L$) the rotor current will lag considerably behind the rotor emf at standstill. Since the rotor emf in any conductor is in phase with the rotating flux, the rotor current in any rotor conductor will not reach its maximum value until the denser part of the rotating flux has passed on. The starting torque of the squirrel-cage induction motor with full load current in the stator winding will therefore

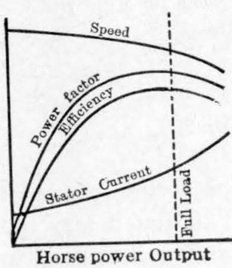


FIG. 221

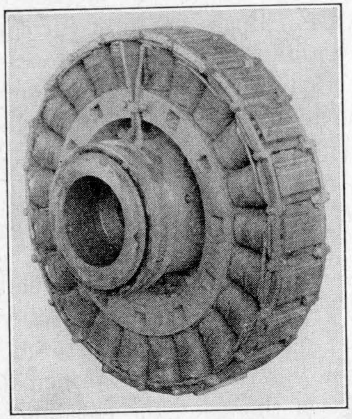
be only a small fraction of the rated full load torque. In the wound rotor induction motor, equipped with rotor slip-ring connections and an external rheostat, resistance (R_e) may be added to each rotor winding so that $\tan \theta \left(= \dfrac{2\,\pi f s L}{R + R_e}\right)$ may be made smaller during the starting period and the starting torque increased. Since an increase of rotor resistance also reduces the rotor current and in this way reduces the rotor torque, only sufficient resistance should be added to the rotor circuit to obtain a maximum torque. This is obtained when the resistance of the rotor circuit is approximately twice its reactance. As the rotor comes up to speed the external resistance may be reduced to zero since the frequency (sf) of the rotor emf decreases as the speed increases.

Though the rotor reactance is directly proportional to the slip the ratio of rotor inductance to rotor resistance may be sensibly fixed in squirrel-cage induction motors so that the maximum torque will come at any desired speed. For this purpose the principal methods of design involve the depths of the slots, the resistance of the conducting material, and sometimes the use of duplex windings of different characteristics. A squirrel-cage rotor can be designed, for example, with a fixed high-resistance rotor which will deliver its maximum torque at standstill but will operate at full load at low efficiency and large slip.

The addition of external resistance to the rotor windings of an induction motor during the starting period serves also to reduce the stator current since the rotor is then not short-circuited. Excessive starting current in a squirrel-cage induction motor with a low rotor resistance must be prevented by connecting resistances or a three-phase auto-transformer with adjustable contacts, called a compensator, between the stator terminals and the three-phase source of power. In some cases induction motors are started without excessive current by connecting the stator windings first in Y and then in Δ.

Starting a Synchronous Motor as an Induction Motor. In starting a synchronous motor as an induction motor the field winding, which contains many more turns than the usual rotor winding, must first be opened in several places so that the emf generated between any two points will not be excessive. In

anticipation of this method of starting, short-circuited copper bars may be built into the pole faces to take the place of a rotor winding. These bars, called a damper winding, will also greatly reduce hunting when the motor is operating as a synchronous motor. Three-phase currents established in the armature of the synchronous motor (operated at reduced terminal potential) will then produce a rotating flux and cause either the armature or the field, depending upon which is the rotor, to revolve in accordance with the induction motor principle. When the rotating member reaches its maximum speed (nearly synchronous speed) the direct-current field circuit is closed and the terminal potential is increased to full line potential. The rotating member will then be pulled into synchronism and the synchronous motor will operate continuously at constant speed. In the synchronous-induction motor the rotor contains two windings: a high-resistance squirrel-cage winding for starting, and a polarized winding which is connected automatically to a direct-current source near synchronism and which pulls the rotor into synchronism.



General Electric Co.

Revolving field of a Three-phase Synchronous Motor Showing Damper Winding for Starting as an Induction Motor and for Prevention of Hunting.

Speed Adjustment of the Three-phase Induction Motor. The inherent speed variation of the induction motor with changes in load (see Fig. 221) resembles that of the direct-current shunt motor; that is, the speed decreases slightly as the load is increased. The speed may be adjusted slightly by changing the magnitude of the terminal potential; a reduction of the terminal potential weakens the rotating flux causing the rotor to revolve at decreased speed for the same electromagnetic torque. In the wound rotor type of induction motor the speed may be adjusted by changing the resistance of the rotor circuit by means of an external rheostat connected to the rotor windings by slip rings; an increase of the

rotor resistance reduces the speed of the rotor. Abrupt changes in speed may be obtained by changing the number of phase sets but this method involves increased expense in the construction of the motor and complicated connections. The speed of two induction motors with their rotors coupled mechanically may be changed as a unit by connecting the stator winding of one motor to the rotor winding of the other motor through slip rings. The motors are then said to be connected in concatenation or cascade. If the number of phase sets in each motor is represented by m_1 and m_2 respectively, four speeds may be obtained as follows: $S_r = \frac{60f}{m_1}(1-s)$ (motor No. 1 operated alone), $S_r = \frac{60f}{m_2}(1-s)$ (motor No. 2 operated alone), $S_r = \frac{60f(1-s)}{m_1+m_2}$ (motors connected in opposition in concatenation), and $S_r = \frac{60f(1-s)}{m_1-m_2}$ (motors connected in conjunction in concatenation). The speed of an induction motor may also be adjusted by changing the frequency of the terminal potential but this is rarely possible.

The Three-phase Induction Generator. If the rotor conductors of a three-phase induction motor are driven mechanically at a higher speed than the rotating flux the rotor emf and current are reversed and the rotor mmf aids the stator mmf. The stator emf may then exceed the stator terminal potential and electric power will be delivered to the line. Since the operation of the machine as an induction generator is dependent upon the production of a rotating flux by an external three-phase source of power the induction generator may not be operated alone but must be connected in parallel with a synchronous generator. The principal advantage of the induction generator relates to its ability to withstand a short circuit at its terminals without serious injury. A short circuit eliminates the source of the rotating flux and therefore causes generator action to cease almost immediately. In some instances induction motors on electric locomotives are driven above synchronous speed when going down grade and furnish regenerative braking.

The Single-phase Induction Motor. If a single-phase current is established in the stator winding of a single-phase induction

motor the net torque developed by the stationary rotor at any instant, as shown in Fig. 222, will be zero. If the rotor be turned mechanically the displacement of the rotor will cause the rotor to develop torque in the direction of displacement as shown in Fig.

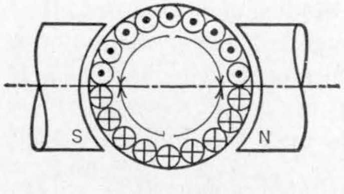


FIG. 222

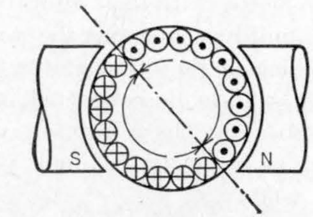


FIG. 223

223. The rotor will then come up to speed and an additional emf will be generated in the rotor conductors owing to their motion in the alternating magnetic flux. The current established by the composite effect of the induced emf and the rotational emf will cause the torque to increase with the speed until a certain speed is reached where a further increase in speed causes the torque to decrease. The speed at which the torque is a maximum depends upon the ratio of the rotor reactance (at rest) to the rotor resistance; the higher the ratio of rotor reactance to rotor resistance, the higher the speed will be at which the torque is a maximum.

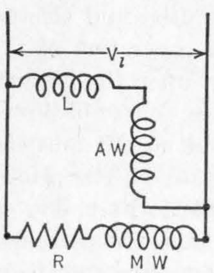
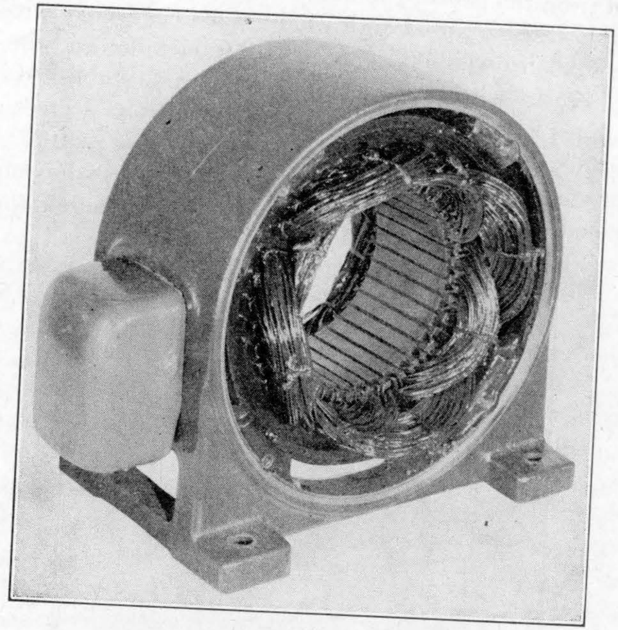


FIG. 224

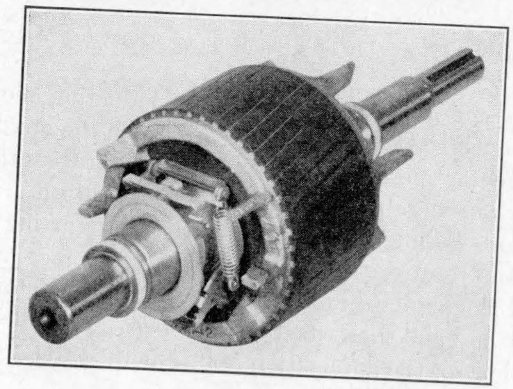
The torque is zero for any ratio of rotor reactance to rotor resistance at a speed slightly less than synchronous speed and when the ratio of rotor reactance to rotor resistance is not greater than unity no motor torque is obtained at any speed. After being started the single-phase induction motor will operate in substantially the same manner as the three-phase induction motor. It may in fact be shown that the composite effect of the stator and rotor currents (with the rotor in motion) is to produce a rotating flux and the operation of the motor may be explained on this basis.

The single-phase induction motor may be made self-starting by means of a split-phase stator winding. An auxiliary winding (AW), in Fig. 224, is placed upon the stator core with its axis



General Electric Co.

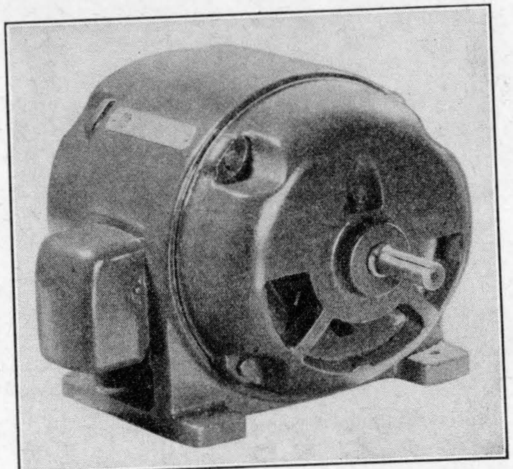
Stator Winding of a Single-phase Capacitor Motor.



General Electric Co.

Cast Aluminum Rotor of a Single-phase Capacitor Motor.

displaced from the axis of the main winding (*MW*) by 90 degrees. During the starting period both windings are connected across the line, the auxiliary winding in series with inductance and the main winding in series with resistance. The currents established in the two windings will then differ in phase by nearly 90 degrees and a rotating flux will be produced as described on page 199. After the rotor comes up to speed the auxiliary winding is disconnected or combined with the main winding and connected across the line.



General Electric Co.

Complete Assembly of a Single-phase Capacitor Motor.

In the capacitor type of single-phase induction motor a condenser is connected permanently in series with the auxiliary winding. This motor operates at better power factor than the inductor type but is considerably larger for the same output. Sometimes the capacitor winding is active only during the starting period and is switched off automatically when the rotor comes up to speed. Very small single-phase induction motors may be started by the shaded-pole principle described on page 167. The efficiency under load is too low for the application of this method to large motors.

Practice problems with answers for Chapter XV will be found on pages 278 to 279.

CHAPTER XVI

THE ALTERNATING-CURRENT SERIES COMMUTATOR MOTOR

Limitations in the Use of Synchronous and Induction Motors. The synchronous motor is not adjustable as to speed, the single-phase motor is not self-starting and the three-phase motor may only be started as an induction motor at low torque. A direct- and an alternating-current source of power is required for synchronous motors (the direct-current generator may be driven by the motor) and synchronous motors must be synchronized with the line potential if started by means of an auxiliary motor. The speed of an induction motor may be adjusted to some extent but the adjustment feature usually involves increased cost and decreased efficiency and rating. Full load starting torque may only be obtained without excessive stator current with a wound rotor three-phase induction motor with adjustable rotor resistance. It is often desirable that an alternating-current motor be employed which will be adjustable as to speed and will furnish heavy starting torque without excessive current. In many instances single-phase power only is available and when an electric railway is supplied from an alternating-current source of power single-phase electrification is preferred because three-phase connections by trolley wire or third rail are more complicated and expensive. In motor-driven devices intended for attachment to house or office circuits it is desirable that the motor be adapted for operation with either direct or alternating current.

The Alternating-current Series Commutator Motor. A direct-current series motor will operate on an alternating-current system since the armature current and the field flux reverse simultaneously giving unidirectional torque. The operation of an unmodified direct-current series motor with an alternating current will be accompanied, however, by excessive heating of the field core, low power factor and destructive commutation. The series commu-

tator motor must therefore be redesigned for use on alternating-current circuits. The heating of the field core is reduced (1) by laminating the field core with iron sheets to reduce the eddy-current loss, (2) by using iron of low hysteresis loss, (3) by increasing the cross-sectional area of the field core and operating the motor at low flux density and (4) by operating the motor when possible on a low-frequency circuit.

The vector diagram of the alternating-current series motor is shown in Fig. 225. The constituent parts of the terminal potential (V_t) required to counterbalance the reactive potentials in the motor circuit are E_a (the generated emf), I_aR_a (the armature

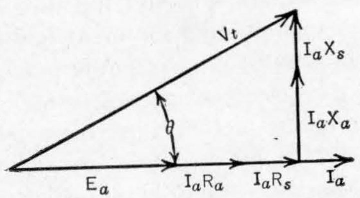


FIG. 225

resistance potential), I_aR_s (the series field resistance potential), I_aX_a (the armature reactance potential) and I_aX_s (the series field reactance potential). Improvement of power factor in the series motor is obtained (1) by making the number of series field turns as small as possible (reduces X_s), (2) by making the field flux as small as possible (reduces X_s), (3) by placing a series compensating winding on the field frame so located that its mmf opposes the armature mmf (reduces X_a) and (4) by operating the motor when possible on a low-frequency circuit (reduces X_a and X_s).

In the alternating-current series motor it is impossible to make the potential between a and b (Fig. 63, page 65) zero at the instant the brush breaks contact with segment No. 1 since the armature conductors connected to segments No. 1 and No. 2 carry an alternating current which is increased by the emf induced by the alternating flux when the two segments are bridged by the brush. Since the current broken when the brush breaks contact with segment No. 1 cannot be made zero, improvement of commutation may only be obtained by making the current flowing from a to b through segment No. 1 as small as possible. This is accomplished

(1) by reducing the alternating field flux and, consequently, the emf induced in the armature conductors short-circuited by the brush, (2) by reducing the number of armature conductors connected between the commutator segments, (3) by introducing resistance in the connections between the commutator segments and the armature conductors and (4) by operating the motor when possible on a low-frequency circuit.

The speed of an alternating-current series motor may be adjusted by connecting resistance in series with the motor or by connecting the motor terminals to the secondary of a transformer with adjustable secondary contacts. It will be noted that the modified series motor will operate on either an alternating-current or a direct-current circuit and for this reason is sometimes called the universal motor. Some alternating-current, single-phase motors are started as series motors and after coming up to speed a centrifugal device disconnects the field winding from the armature circuit and short-circuits the armature. The motor will then operate as a single-phase induction motor at sensibly constant speed.

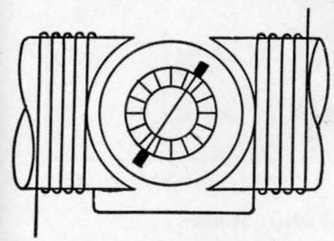


FIG. 226

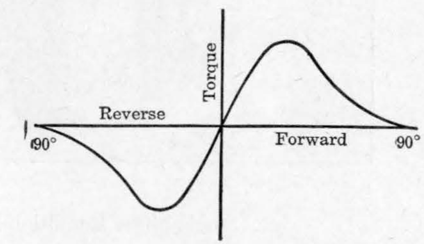
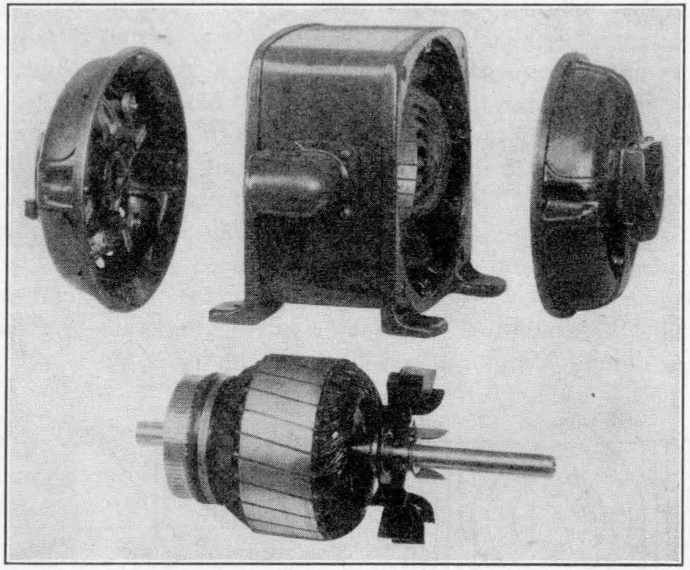


FIG. 227

The Alternating-current Repulsion Motor. The single-phase alternating-current repulsion motor, connected as shown in Fig. 226, operates in the same manner as the single-phase series motor. It will be noted that the field winding is connected across the line, and the two brushes are located off center and short-circuited. The armature currents, instead of being conducted through the armature as in the series motor, are induced in the armature by the alternating field flux. The variation in starting torque with brush position is shown in Fig. 227. The direction of the torque is in the direction of the brush shift and the motor may be reversed

by shifting the brushes from one side of the interpolar plane to the other.

This type of alternating-current commutator motor is better adapted to starting motors which turn into induction motors when running because the commutator only must be short-circuited,



General Electric Co.

Single-phase Repulsion-induction Motor.

the field winding remaining connected as it was. This type of motor is also better adapted to use on high potential circuits because the armature may still operate at low potential with no consequent difficulties with commutation and insulation. A compensating field winding, located at an angle of 90 degrees from the main field winding and connected in series with it, improves the power factor as in the series alternating-current motor. Reversal of the terminals of this auxiliary field winding reverses the direction of rotation of the motor. This method of reversal is usually more convenient than by shifting the brushes.

Practice problems with answers for Chapter XVI will be found on page 279.

TABLES

Copper Wire Table*

Size	Diameter	Area	Resistance at 25 C		Weight
American Wire Gage	Mils	Circular mils	Ohms per 1000 feet	Ohms per mile	Pounds per 1000 feet
18	40.2	1,620	6.51	34.4	4.92
16	50.8	2,580	4.09	21.6	7.82
14	64.1	4,110	2.58	13.6	12.4
12	80.8	6,530	1.62	8.55	19.8
10	102	10,400	1.02	5.39	31.4
8	128	16,500	0.641	3.38	50.0
6	162	26,300	0.403	2.13	79.5
5	182	33,100	0.319	1.68	100
4	204	41,700	0.253	1.34	126
3	260	52,600	0.205	1.08	163
2	292	66,400	0.162	0.858	205
1	332	83,700	0.129	0.681	258
0	373	106,000	0.102	0.540	326
00	418	133,000	0.0811	0.428	411
000	470	168,000	0.0642	0.339	518
0000	528	212,000	0.0509	0.269	653
....	630	300,000	0.0360	0.190	926
....	728	400,000	0.0270	0.142	1240
....	814	500,000	0.0216	0.114	1540
....	893	600,000	0.0180	0.0949	1850
....	964	700,000	0.0154	0.0814	2160
....	1031	800,000	0.0135	0.0712	2470
....	1093	900,000	0.0120	0.0633	2780
....	1152	1,000,000	0.0108	0.0570	3090
....	1209	1,100,000	0.00981	0.0518	3400
....	1263	1,200,000	0.00899	0.0475	3710
....	1315	1,300,000	0.00830	0.0438	4010
....	1364	1,400,000	0.00770	0.0407	4320
....	1412	1,500,000	0.00719	0.0380	4630
....	1459	1,600,000	0.00674	0.0356	4940
....	1504	1,700,000	0.00634	0.0335	5250
....	1548	1,800,000	0.00599	0.0316	5560
....	1590	1,900,000	0.00568	0.0300	5870
....	1631	2,000,000	0.00539	0.0285	6180

* For wires larger than No. 4 the values given are for stranded wires and the diameters are outside diameters.

Resistivity (ρ) in Ohms per Mil-foot and Temperature Coefficient of Resistance (α) of Copper at Various Temperatures

Degrees C	ρ	α	Degrees C	ρ	α
0	9.55	0.00427	25	10.6	0.00385
15	10.2	0.00401	30	10.8	0.00378
20	10.4	0.00393	50	11.6	0.00352

Current Capacity in Amperes

Not more than three copper* conductors in one raceway or cable. Room temperature is 30 C.† See page 15 for explanation of type letters.

Size AWG or CM‡	Type Letter						
	R RW	RP, RPT, RU, SN	RH RHT	Paper V, AVB	AVA AVL	AI	A
14	15	18	22	23	28	29	32
12	20	23	27	29	36	38	42
10	25	31	37	38	47	49	54
8	35	41	49	50	60	63	71
6	45	54	65	68	80	85	95
5	52	63	75	78	94	99	110
4	60	72	86	88	107	114	122
3	69	83	99	104	121	131	145
2	80	96	115	118	137	147	163
1	91	110	131	138	161	172	188
0	105	127	151	157	190	202	223
00	120	145	173	184	217	230	249
000	138	166	199	209	243	265	284
0000	160	193	230	237	275	308	340
250	177	213	255	272	315	334	372
300	198	238	285	299	347	380	415
350	216	260	311	325	392	419	462
400	233	281	336	361	418	450	488
500	265	319	382	404	468	498	554
600	293	353	422	453	525	543	612
700	320	385	461	488	562	598	668
750	330	398	475	502	582	621	690
800	340	410	490	514	600	641	720
900	360	434	519	556	...	...	...
1000	377	455	543	583	681	730	811
1250	409	493	589	643	...	...	...
1500	434	522	625	698	784	...	...
1750	451	544	650	733	...	...	...
2000	463	558	666	774	839	...	...

* The current capacity of insulated aluminum wires is 84 per cent of that given for copper.
† Correction factors for room temperatures exceeding 30 C are given on page 301 of the National Electrical Code. ‡ ,000 omitted.

Currect Capacity in Amperes

Single copper* conductor in free air. Room temperature is 30 C.† See page 15 for explanation of type letters.

Size AWG or CM‡	Type Letter							
	R	RP	RH RHT	V AVB	AVA	AI	A	SB SBW
14	20	24	29	30	39	40	43	23
12	26	31	37	40	51	52	57	30
10	35	42	50	54	65	69	75	40
8	48	58	69	71	85	91	100	53
6	65	78	94	99	119	126	134	70
5	76	92	110	115	136	145	158	80
4	87	105	125	133	158	169	180	90
3	101	122	146	155	182	194	211	100
2	118	142	170	179	211	226	241	125
1	136	164	196	211	247	264	280	150
0	160	193	230	245	287	306	325	200
00	185	223	267	284	331	354	372	225
000	215	259	310	330	384	410	429	275
0000	248	298	358	383	446	476	510	325
250	280	338	403	427	495	528	562	350
300	310	373	446	480	555	592	632	400
350	350	421	504	529	612	653	698	450
400	380	457	547	575	665	710	755	500
500	430	517	620	660	765	814	870	600
600	480	577	691	738	857	912	970	680
700	525	632	756	813	942	1003	1065	760
750	545	655	785	846	981	1044	1118	800
800	565	680	815	879	1020	1085	1150	840
900	605	728	872	941	....	....	....	920
1000	650	782	936	1001	1163	1238	1332	1000
1250	740	890	1066	1131	....	....	....	....
1500	815	980	1174	1261	1452	....	....	1360
1750	890	1070	1282	1370	....	....	....	....
2000	960	1155	1383	1472	1713	....	....	1670

* The current capacity of insulated aluminum wires is 84 per cent of that given for copper.
† Correction factors for room temperatures exceeding 30 C are given on page 302 of the National Electrical Code. ‡ ,000 omitted.

Resistivity (ρ) in Microhms per Cm. Cube and Temperature Coefficient of Resistance (α) of Certain Conductors

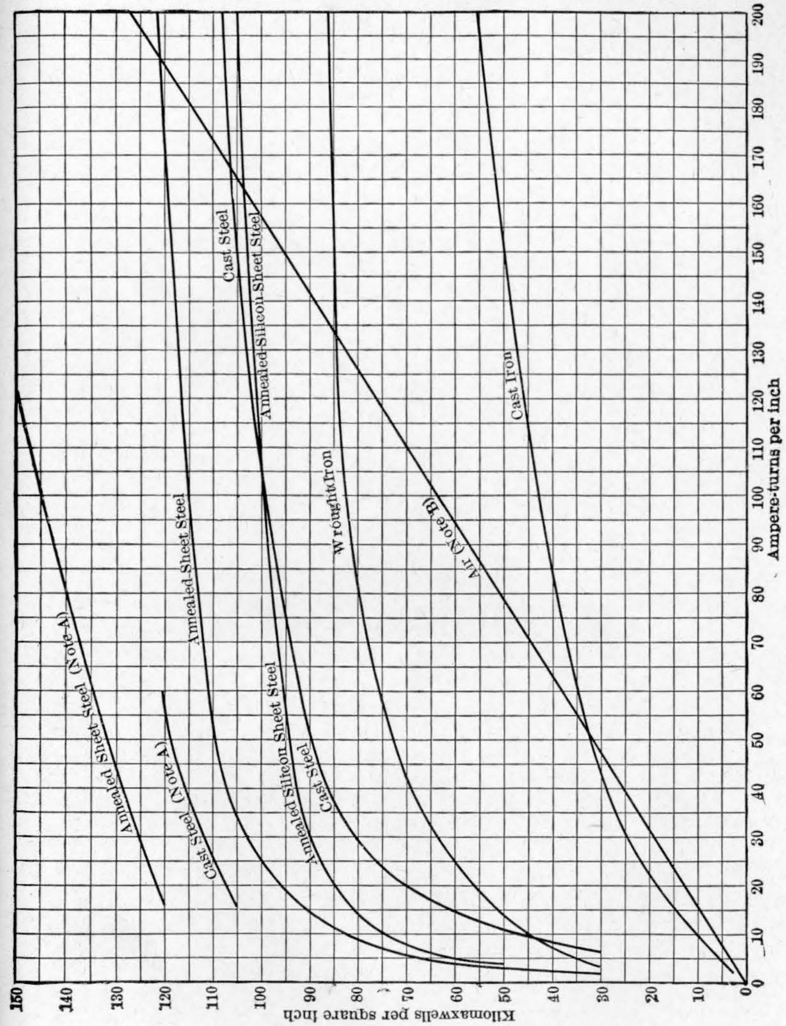
(Temperature is 20 C unless otherwise specified)

Material	ρ	α	Material	ρ	α
Aluminum	2.688	0.00403	Mercury....	95.8	0.00089
Antimony..	39.1 at 0	0.0036 at 0	Molybdenum	5.08 at 0	0.0047 (0–100)
Barium....	9.8	0.0033	Monel metal.	42	....
Beryllium..	10.1	....	Nickel......	7.8	0.00537 (20–100)
Bismuth....	120	0.004	Osmium.....	9.5	0.0033
Carbon.....	3500 at 0	−0.0009 at 0	Palladium...	11	....
Calcium....	4.59	0.00364 (0–600)	Platinum....	9.83 at 0	0.003 at 0
Cerium.....	78	....	Potassium...	6.1 at 0	0.0055 at 0
Cesium.....	19 at 0	....	Rhodium....	5.11 at 0	0.0043 at 0
Chromium..	2.6 at 0	....	Silver.......	1.629 at 18	0.0038
Cobalt.....	9.7	0.00658 (0–100)	Sodium.....	4.3 at 0	0.0054
Copper.....	1.724	0.00393	Strontium...	24.8	....
Gold.......	2.44	0.0034	Tantalum...	15.5	0.0031
Graphite...	800 at 0	....	Tellurium...	2×10^5	....
Iron.......	9.8	0.0065 (0–100)	Thallium....	17.6 at 0	0.0040 at 0
" cast....	79–104	....	Thorium....	18	0.0021 (20–1800)
Lead......	22.0	0.0039	Tin.........	11.5	0.0042
Lithium....	8.55 at 0	0.0047 at 0	Titanium....	3.0	....
Magnesium	4.46	0.0040	Tungsten....	5.5	0.0047 (0–100)
Manganese	5	....	Zinc........	5.75 at 0	0.0037 at 0

Resistivity (ρ) in Megohms per Cm. Cube and Dielectric Constant (k) of Certain Insulators at Room Temperature

Material	ρ	k	Material	ρ	k
Alcohol, ethyl.	0.3	5.0–54.6	Oil, olive.....	5×10^6	3.11
" methyl.	0.14	31.2–35.0	" paraffin...	10^{10}	....
Amber.......	5×10^{10}	......	" petroleum.	2×10^{10}	2.13
Amylacetate..	....	4.81	Paper........	10^4–10^9	1.7–3.8
Asbestos paper	1.6×10^5	2.7	Paraffin......	5×10^{10}–5×10^{12}	1.9–2.3
Asphalt......	....	2.7	Porcelain.....	3×10^8	4.4
Bakelite......	10^5–10^{10}	4.5–5.5	Quartz.......	10^8–5×10^{12}	4.7–5.1
Beeswax......	6×10^8	....	Rosin........	7×10^9–5×10^{10}	2.5
Cellophane...	....	8	Rubber, hard.	3×10^{10}–10^{12}	2.0–3.5
Celluloid.....	2×10^4	13.3	Sealing wax...	10^9–8×10^9	....
Cellulose acetate.....	....	5	Selenium.....	0.06	6.1–7.4
Glass........	5×10^5–10^{10}	5.5–9.1	Shellac.......	10^{10}	3.0–3.7
Glycerin......	....	56.2	Silica, fused...	10^8–10^{13}	3.5–3.6
Gutta percha..	3×10^4	2.9	Slate........	10^2–10^4	6.6–7.4
Ice..........	720	86	Sulphur......	8×10^9–10^{11}	2.9–3.2
Ivory........	200	....	Turpentine...	....	2.23
Marble.......	10^3–10^5	8.3	Water, dist....	0.5	81
Mica.........	4×10^7–2×10^{11}	5–7	Wood, paraffined..	3×10^4–4×10^7	4.1

Multiply " microhms per cm. cube " by 6.01 to obtain " ohms per mil-foot."



Note A. Multiply abscissa scale by 10.
Note B. Multiply abscissa scale by 200.

Conversion Factors

Multiply	by	to obtain
Ampere turns per inch	0.394	ampere turns per cm.
Ampere turns per cm.	2.54	ampere turns per inch.
Kilomaxwells per sq. inch	155	gausses.
Gausses	6.45×10^{-3}	kilomaxwells per sq. in.

PRACTICE PROBLEMS

Chapter I

1. A series circuit contains the emf's and resistances shown in Fig. 228. Determine (**a**) the resultant emf, (**b**) the resultant

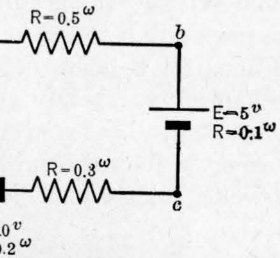


FIG. 228

resistance, (**c**) the current, and (**d**) the respective potentials between a–b, b–c, c–d, and d–a.

Ans. (**a**) 30 volts, (**b**) 1.5 ohms, (**c**) 20 amperes, and (**d**) $V_{ab} = -10$, $V_{bc} = -7$, $V_{cd} = 0$, and $V_{da} = +17$ volts.

2. Two batteries and a resistance of 2 ohms are connected in series as shown in Fig. 229. Battery A has an emf of 50 volts and an internal resistance of 0.5 ohm. The emf and resistance

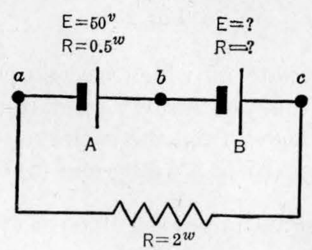


FIG. 229

of battery B are unknown. When battery B is connected in conjunction with battery A (as shown in the figure) the potential between a and b is $+37.8$ volts. When battery B is connected in

opposition to battery A the potential between a and b is +44 volts. Determine (a) the emf and (b) the resistance of battery B.

Ans. (a) 17 volts and (b) 0.247 ohm.

3. A direct-current generator converts mechanical energy into electric energy at a rate of 1200 watts when its armature current is 10 amperes. With the same armature current electric energy is converted into heat energy within the armature at a rate of 60 watts. Determine (a) the emf generated in the armature and (b) the armature resistance between terminals. If operated under the above conditions for 8 hours determine (c) the energy converted from mechanical energy into electric energy, (d) the electric energy converted into heat energy within the armature, and (e) the electric energy delivered from the terminals.

Ans. (a) 120 volts, (b) 0.6 ohm, (c) 9.6 kwhrs, (d) 0.48 kwhr, and (e) 9.12 kwhrs.

4. A resistance of 4.2 ohms is connected between the terminals of a storage battery as shown in Fig. 230. Determine (a) the rate at which chemical energy is converted into electric energy within

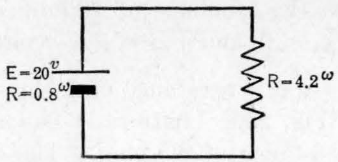


FIG. 230

the battery, (b) the rate at which electric energy is converted into heat energy within the battery, and (c) the rate at which electric energy is delivered from the battery.

Ans. (a) 80 watts, (b) 12.8 watts, and (c) 67.2 watts.

5. What emf must be impressed upon a storage battery of 6 volts emf and 0.1 ohm internal resistance to convert 0.5 kilowatt-hour into chemical energy in 8 hours?

Ans. 7.04 volts.

6. Given the circuit shown in Fig. 231, how much resistance (a) must be connected between a and b to make the power absorbed

by a–b a maximum? Under these conditions determine (b) the potential from a to c and (c) the total power output of the part a–d.

Ans. (a) 8 ohms, (b) 7.5 volts, and (c) 33.2 watts.

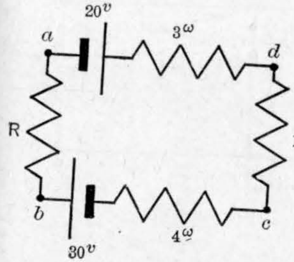


FIG. 231

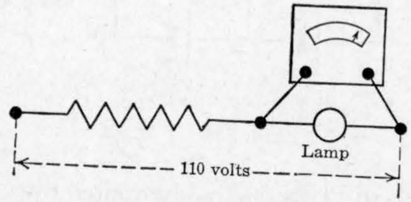


FIG. 232

7. A miniature incandescent lamp of 50-ohms resistance is connected in series with an unknown resistance across a 110-volt direct-current line as shown in Fig. 232. A voltmeter of 200-ohms resistance, connected between the terminals of the lamp, reads 8.2 volts. Determine (a) the potential between the lamp terminals when the voltmeter is removed and (b) the voltmeter reading with the voltmeter connected as indicated and the lamp burnt out.

Ans. (a) 10.1 volts, and (b) 31.6 volts.

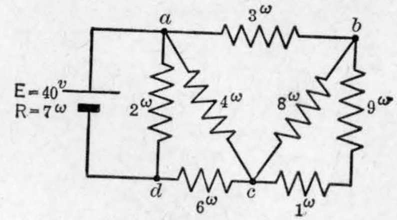


FIG. 233

8. An emf of 40 volts is impressed upon the circuit shown in Fig. 233. Determine (a) the equivalent resistance between a and d and (b) the current in the 8-ohm resistance.

Ans. (a) 1.62 ohms, and (b) 0.17 ampere.

9. Three batteries, A, B, and C, are connected as shown in Fig. 234. Determine the current in each battery.

Ans. $I_A = 1.58$, $I_B = 2.32$, and $I_C = 3.90$ amperes.

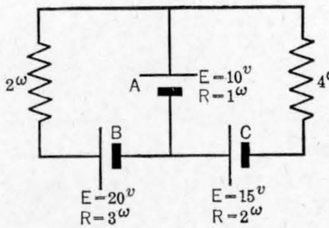


FIG. 234

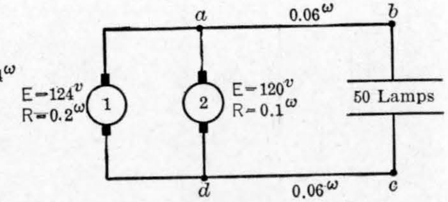


FIG. 235

10. Two separately excited direct-current generators, operating in parallel, supply power to a group of 50 incandescent lamps connected in parallel as shown in Fig. 235. The generated emf of No. 1 is 124 volts and the generated emf of No. 2 is 120 volts. The resistance of No. 1 between terminals is 0.2 ohm, and the resistance of No. 2 between terminals is 0.1 ohm. Each lamp has a resistance of 100 ohms and the connecting line wires, ab and cd, each have a resistance of 0.06 ohm. Determine (**a**) the armature current of generator No. 1, (**b**) the armature current of generator No. 2, (**c**) the line current, (**d**) the terminal potential at each generator, and (**e**) the terminal potential at the lamps.

Ans. (**a**) 31.85 amperes, (**b**) 23.65 amperes, (**c**) 55.5 amperes, (**d**) 117.6 volts, and (**e**) 111.0 volts.

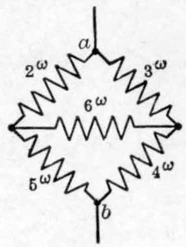


FIG. 236

11. Determine the current in each section of the connection shown in Fig. 236 when the potential between a and b is 50 volts.

What is the equivalent resistance of the connection between a and b?

Ans. $I_2 = 7.70$, $I_3 = 6.70$, $I_4 = 7.48$, $I_5 = 6.92$, $I_6 = 0.78$ amperes and $R_{ab} = 3.47$ ohms.

12. Given the two batteries connected as shown in Fig. 237. For what value of R will the power output of each battery be the same?

Ans. 0.25 ohm and zero.

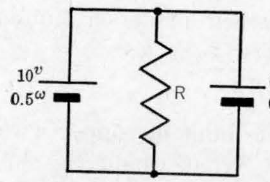


FIG. 237

13. Given the connection shown in Fig. 238, determine the potential from b to c when the potential from a to c is -115 volts.

Ans. $V_{bc} = -79$ volts.

14. The resistance of the copper winding of the armature of a motor at 20 C is 0.16 ohm. After the motor has been in service for several hours, the armature resistance is found to be 0.20 ohm. Determine the corresponding temperature of the armature winding.

Ans. 83.6 C.

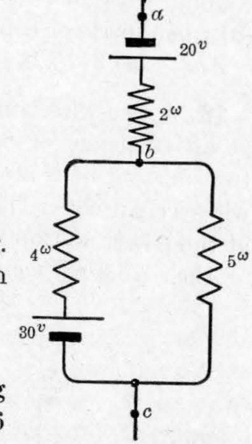


FIG. 238

15. An electric heater is to be constructed of nickel-chromium wire 0.03 inch in diameter and 100 microhms per centimeter cube resistivity when hot. How many feet of this wire should be wound on the heater if it is to absorb 600 watts when connected across a 115-volt line?

Ans. 33 feet.

16. A No. 10 (A.W.G.) iron wire is covered with a copper coating, 0.002 inch in thickness. The resistivity of the iron is 50 ohms per mil-foot and of the copper 10.4 ohms per mil-foot, both at 20 C.

Determine the resistance of this copper-covered wire per mile at 20 C.

Ans. 18.3 ohms.

17. Given the following data regarding aluminum and copper wire: aluminum — resistivity, 17.1 ohms per mil-foot at 20 C; weight, 0.0972 pound per cubic inch; cost, 28 cents per pound; copper — resistivity, 10.4 ohms per mil-foot at 20 C; weight, 0.321 pound per cubic inch; cost, 14 cents per pound. Determine the respective costs of a transmission line 2000 feet in length of 0.4-ohm resistance at 20 C, (**a**) when made of aluminum, and (**b**) when made of copper.

Ans. (**a**) \$175.28 and (**b**) \$176.12.

18. A two-wire transmission line built of copper wire operates at an efficiency of 85 per cent. What would the efficiency of transmission be if aluminum wires of the same size as the copper wires were used? The power delivered to the line and the potential at the power station remain constant.

Ans. 75.3 per cent.

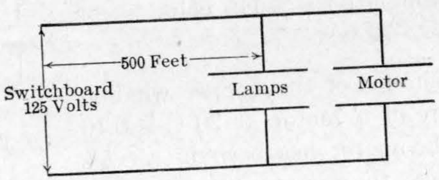


Fig. 239

19. Energy is transmitted from a switchboard to a lamp and a motor load as shown in Fig. 239. Two No. 2 wires (0.162 ohm per 1000 feet) connect the load to the switchboard. The group of lamps takes 30 amperes and the motor 20 amperes from the line. Determine (**a**) the power supplied to the lamps, (**b**) the power supplied to the motor, (**c**) the power lost in the line wires, (**d**) the total power taken from the switchboard, and (**e**) the efficiency of the transmission line.

Ans. (**a**) 3507 watts, (**b**) 2338 watts, (**c**) 405 watts, (**d**) 6250 watts, and (**e**) 93.5 per cent.

20. Energy is transmitted from a 230-volt generator to a factory over a transmission line of 0.1-ohm resistance. When the power received at the factory is 50 kilowatts, what is (**a**) the line current, (**b**) the line potential at the factory, and (**c**) the efficiency of transmission?

Ans. (**a**) 243.1 amperes, (**b**) 205.7 volts, and (**c**) 89.4 per cent.

21. What size (A.W.G.) of RP rubber-covered copper wire in conduit should be used to transmit 30 kilowatts to a motor located 350 feet from a switchboard if the line potential at the switchboard is 237 volts and the line potential at the motor must not be less than 230 volts? The temperature of the wire is 50 C, and the room is 30 C. The wire must comply with all requirements of the National Electrical Code.

Ans. No. 000.

22. What is the most economical size of copper wire for a transmission line which conducts 50 amperes during 3000 hours of each year if copper costs 14 cents per pound, electric energy costs 2 cents per kilowatthour, and the annual interest on the capital invested in the copper, including capital interest, depreciation, and taxes, is 8 per cent?

Ans. 217,000 circular mils.

23. An aluminum transmission line 1 mile in length conducts 100 amperes during 3000 hours of each year. The aluminum costs 23 cents per pound and weighs 0.0972 pound per cubic inch. The electric energy costs 2 cents per kilowatthour and the annual interest, depreciation, and taxes total 8 per cent. The line potential at the load is 550 volts. If the most economical size (nearest A.W.G.) is installed what will the efficiency of transmission be at a line temperature of 30 C?

Ans. 95.9 per cent.

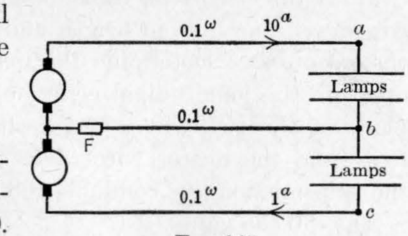


Fig. 240

24. An Edison three-wire system is operated with an unbalanced load as shown in Fig. 240. The line potentials at the two generators are adjusted to make the line potential at each lamp load 110 volts. Determine the line potential at each lamp load after a fuse (F) in the neutral wire opens the circuit, the line potentials at the generators remaining the same as before.

Ans. V_{ab} equals 20.1 volts and V_{bc}, 200.7 volts.

25. Determine the transmission efficiency of an Edison three-wire system under the following conditions: terminal potential of each generator, 115 volts; resistance of each transmission wire, 0.1 ohm; current in the upper wire (Fig. 12, page 18), 25 amperes to the right; current in the neutral wire, 7 amperes to the left.

Ans. 98.0 per cent.

26. Given the unbalanced Edison three-wire system shown in Fig. 241. The lamps in each group are connected in parallel. Each lamp has a resistance of 200 ohms, which is to be assumed

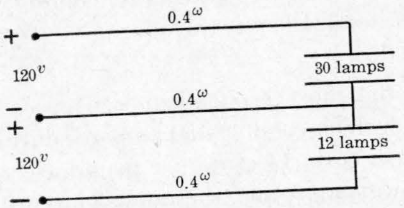


FIG. 241

constant. Determine (**a**) the magnitude and direction of the current in the neutral wire, and (**b**) the potential between the terminals in each group of lamps.

Ans. (**a**) 9.2 amperes (to left), and (**b**) $V_A = 109.7$ volts and $V_B = 120.8$ volts.

Chapter II

27. A direct-current transmission line consists of two straight wires each one mile in length and located 2 feet apart (between their centers). Determine the magnetic flux density at a point opposite the longitudinal center of the transmission line, in the plane of the two wires, and located at a normal distance of 1 foot from the nearer wire (3 feet from the further wire) when the transmission line conducts 100 amperes.

Ans. 0.438 gauss.

28. Two straight parallel wires, each conducting 500 amperes in opposite directions, are located on the back of a switchboard as shown in Fig. 242 (elevation view). Determine (**a**) the magnetic flux density due to these currents at a point (A) in an electrical instrument on the front of the switchboard and (**b**) the

force with which the upper wire repels each foot in length of the lower wire. The permeability of all parts is unity and the wires may be assumed to be of infinite length and negligible cross section.

Ans. (**a**) 3.94 gausses, and (**b**) 7500 dynes.

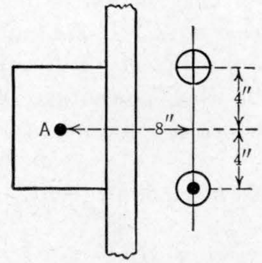


FIG. 242

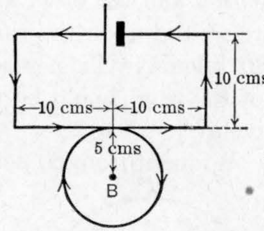


FIG. 243

29. Determine the magnetic flux density at the point B in Fig. 243 due to a current of 20 amperes flowing as shown in the figure. The current path through the battery is to be assumed a straight line.

Ans. 2.93 gausses.

30. Three straight wires, each 30 centimeters in length and having the same resistance, form an equilateral triangle as shown in Fig. 244. The total current flowing in at (a) and out at (b) is 18 amperes. Determine the magnetic flux density, due to the triangle only, at a point in the plane of the triangle at its center.

Ans. Zero.

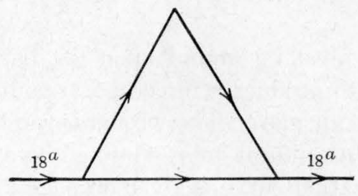


FIG. 244

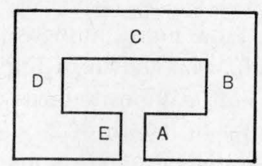


FIG. 245

31. Determine the number of ampere turns required to establish a magnetic flux of one million maxwells in the magnetic circuit shown in Fig. 245. The area of the magnetic circuit perpendicular to the flux is 12.5 square inches throughout. The

part, *ABCDE*, is made of cast steel and has an average length of 50 inches. The part, *AE*, is an air gap 1.5 inches in length.

Ans. 39,000 ampere turns.

32. A ring, 10 inches in mean diameter, consists of two sections welded together as shown in Fig. 246. One section is made of wrought iron and the other section of cast steel. If 1743 ampere turns are wound upon the ring and the flux density in the ring is to be 80 kilomaxwells per square inch what percentage of the length of the ring should be made of wrought iron and cast steel respectively?

Ans. Wrought iron, 50 per cent; cast steel, 50 per cent.

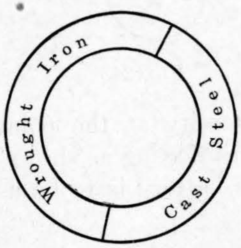


FIG. 246

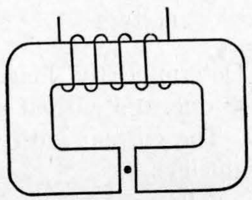


FIG. 247

33. Five hundred turns of wire conducting 7 amperes are wound on a wrought iron core with a 0.25-inch air gap as shown in Fig. 247. The mean length of the flux path in the iron is 40 inches and its cross-sectional area is 6 square inches. Determine the force per inch length on a straight wire located in the air gap and conducting 0.5 ampere.

Ans. 806 dynes.

34. How many ampere turns must be wound upon the bar of wrought iron shown in Fig. 247 to produce a force of 200 pounds between the opposite faces of the air gap? The wrought iron bar has a mean length of 20 inches, a uniform cross-sectional area of 4 square inches, and its magnetization curve is given on page 223. The air gap has a length of 0.25 inch and its cross-sectional area may be assumed to be the same as that of the iron.

Ans. 5250 ampere turns.

35. Given the magnetic circuit of a lifting magnet as shown in Fig. 248. Both the upper and lower members are made of cast

steel (magnetization curve on page 223). The mean length of the magnetic flux in the upper member is 30 inches and in the lower member 12 inches. Each air gap (where the lower member makes contact with the upper member) may be taken as 0.02

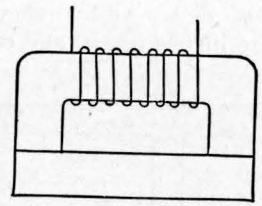


FIG. 248

inch. Each area of contact and the mean area perpendicular to the magnetic flux is 15 square inches. How many ampere turns must be wound on the upper member to support a weight of 1 ton, including the weight of the lower member?

Ans. 1670 ampere turns.

36. A lifting magnet of the type shown in Fig. 248 is to be designed to support a weight, including the lower member, of 1600 pounds. It is to be wound with 980 ampere turns and each air gap is to be assumed 0.01 inch in length. Each surface contact is to be 10 square inches and the total length of the magnetic circuit in the iron is to be 20 inches. What kind of iron (page 223) should be specified for the construction of the magnet?

Ans. Cast steel.

37. The cross section of the iron core of a magnetic relay is shown in Fig. 249. The plunger (*AB*) and the magnetic shell (*CDFD′C′*) are made of cast steel of the following dimensions: length (*AB*), 5 inches; sectional area, perpendicular to the paper (*AB*), 0.8 square inch; length (*BCDF*) and (*BC′D′F*), each 9 inches; sectional area (*BCDF*) and (*BC′D′F*), each 0.5 square inch; air gap (*AF*), 0.1 inch. How many ampere turns must be wound on *AB* (cross-hatched section shows section of coil) to cause the plunger to

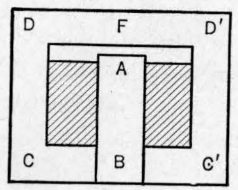


FIG. 249

rise and close air gap (AF) if the plunger weighs 1.2 pounds and friction is neglected?

Ans. 355 ampere turns.

38. A magnetic circuit made of annealed sheet steel has the dimensions shown in Fig. 250. The cross-sectional area of members A and B is 5 square inches (each) and of member C, 4 square

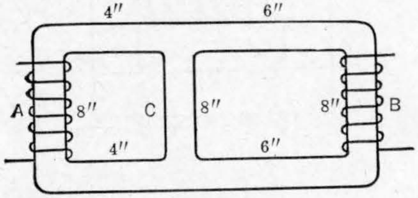


Fig. 250

inches. The number of turns on member A is 50 and on member B, 80. If the flux density in member C is to be 100 kilomaxwells per square inch determine the currents to be established in coils A and B respectively so that the flux density in member B will be zero.

Ans. $I_A = 6.7$ amperes and $I_B = 2.5$ amperes.

39. The hysteresis loop of a sample of iron is plotted to the following scale: abscissa, 1 centimeter equals 10 ampere turns per centimeter; and ordinate, 1 centimeter equals 2000 gausses. When the maximum flux density is 11,500 gausses the area of the loop is found to be 3 square centimeters. The volume of the iron sample is 100 cubic centimeters. If the sample is revolved in a magnetic field of 11,500 gausses flux density at the rate of 60 revolutions per second determine the power lost in the iron due to hysteresis.

Ans. 3.6 watts.

Chapter III

40. A rotating disc, r centimeters in radius, is located at the center of a long air-core solenoid with its axis of rotation coinciding with the axis of the solenoid as shown in Fig. 251. The solenoid has n turns per centimeter length and it may be assumed that the flux density due to the solenoid is uniform throughout the disc.

In the figure, G is a galvanometer, R is an unknown resistance, A is a brush resting on the periphery of the disc, B is a brush resting on the disc shaft, C and D are the end terminals of the

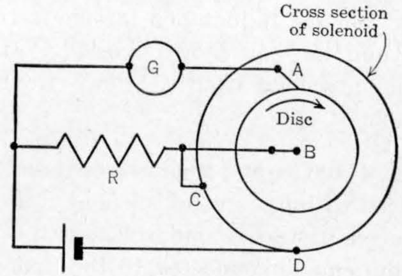


Fig. 251

solenoid. When the disc revolves at a speed of S rpm, the galvanometer reads zero. Determine the value of R. The battery emf is unknown.

Ans. $R = \dfrac{6.57\ r^2nS}{10^{10}}$ ohms.

41. A long solenoid of wire of 0.01-henry self-inductance has a single layer of double-cotton covered copper wire. The core is air and the diameter of the wire, including the insulation, is 0.019 inch. Determine the volume of the core.

Ans. 1850 cubic cm.

42. A solid cast steel ring 8 inches in mean diameter and 2 square inches in cross-sectional area is wound uniformly with 500 turns of wire. Find the inductance of this winding when carrying 0.25 ampere.

Ans. 1.0 henry.

43. Referring to Fig. 249 accompanying Problem 37, determine the inductance of 200 turns of wire surrounding the plunger (AB) when conducting a current of 2 amperes and with the air gap open (0.1 inch).

Ans. 0.0094 henry.

44. A coil having a concentrated winding of 1000 turns has a self-inductance of 0.05 henry. What is the magnetic energy associated

with a current in this coil which produces a flux of 2000 maxwells?

Ans. 0.004 joule.

45. An emf of 20 volts is impressed upon a coil of 0.5-ohm resistance and 0.25-henry inductance for one second. The emf is then removed and the coil short-circuited. Find the current flowing in the coil one second after it is short-circuited.

Ans. 4.68 amperes.

46. A solenoid of 100 turns, 2-ohms resistance and 0.1-henry inductance is placed within a second solenoid of 500 turns. What emf will be induced in the second solenoid 0.1 second after a battery of 10 volts emf is connected to the first solenoid? The second solenoid is open-circuited and the resistance of the battery is to be neglected.

Ans. 6.8 volts.

47. The magnetic energy associated with an electric circuit of 0.2-ohm resistance when conducting a current of 4 amperes is 0.8 joule. What emf must be impressed upon this circuit to establish a current of 3 amperes 0.1 second after the emf is impressed?

Ans. 3.31 volts.

48. The field winding of a dynamo has a resistance of 25 ohms and contains 1000 turns. When an emf of 100 volts is impressed upon this winding, the field flux produced is 8 million maxwells. (a) What is the inductance of the winding? (b) What will the current in the field winding be 0.6 of a second after the emf is impressed? (c) What is the ultimate value of the field current? (d) How much energy is stored in the magnetic circuit of the dynamo when the field current has reached its ultimate value? (e) If a non-inductive resistance of 1000 ohms is connected in parallel with the field winding and the emf of 100 volts impressed upon the resulting parallel circuit is suddenly removed, what will be the initial potential between the terminals of the 1000-ohm resistance?

Ans. (a) 20 henrys, (b) 2.11 amperes, (c) 4 amperes, (d) 160 joules, and (e) 4000 volts.

49. When an emf of 10 volts is impressed upon a coil of wire of unknown resistance and inductance the initial rate of change of the current is 100 amperes per second and the ultimate value of the current is 10 amperes. Determine the current flowing in the coil of wire 0.1 second after the emf is impressed.

Ans. 6.32 amperes.

50. When an emf of 6 volts is impressed upon a coil of wire the initial rate of change of the flux linking the coil is 600,000 maxwells per second. The ultimate flux linking the coil is 100,000 maxwells and the ultimate magnetic energy associated with the coil is 2.5 joules. Determine the resistance and self-inductance respectively of the coil.

Ans. $R = 1.2$ ohms and $L = 0.2$ henry.

51. How much emf must be impressed upon a coil of wire of 3-ohms resistance and 0.4-henry self-inductance to convert 5 joules of electric energy into magnetic energy in 0.2 second?

Ans. 19.3 volts.

52. Two automobile head lamps are connected in parallel to a storage battery as shown in Fig. 252. Each lamp has a resistance of 2 ohms, the emf of the storage battery is 6 volts, the self-inductance of the connecting wires and the frame is 0.1 henry, and the resistance of the battery and all connections is negligible. If one of the head lamps should burn out suddenly (opening in its filament), determine (a) the consequent initial potential across the other lamp, (b) the consequent initial rate of change of the battery current, and (c) the time required for the potential across the remaining lamp to return to 6.1 volts.

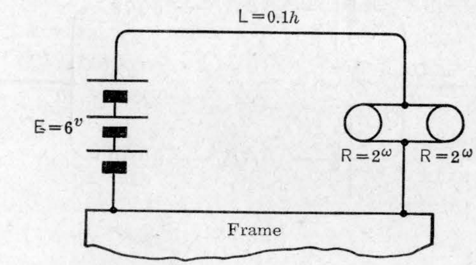


FIG. 252

Ans. (a) 12 volts, (b) 60 amperes per second (decreasing), and (c) 0.204 second.

53. Three coils of wire are wound upon an air core in such a manner that all the flux due to each coil links the other two coils. No. 1 coil has a self-inductance of 0.1 henry and a resistance of 1 ohm; No. 2 coil, 0.2 henry and 2 ohms; No. 3 coil, 0.4 henry and 4 ohms. The three coils are connected in series; No. 1 and No. 3 in conjunction, and No. 2 in opposition to those two. How much emf must be impressed upon this assembly of coils to establish in them a current of 10 amperes in 0.01 second?

Ans. 288 volts.

54. A coil of wire of 2-ohms resistance and 0.4-henry self-inductance is to be connected across the terminals of a storage battery of 10 volts constant emf and negligible internal resistance. At the instant 0.3 second after the connection is made determine the rate of energy (**a**) converted from chemical to electric energy, (**b**) converted from electric to thermal energy, and (**c**) converted from electric to magnetic energy.

Ans. (**a**) 38.8 watts, (**b**) 30.1 watts, and (**c**) 8.68 watts.

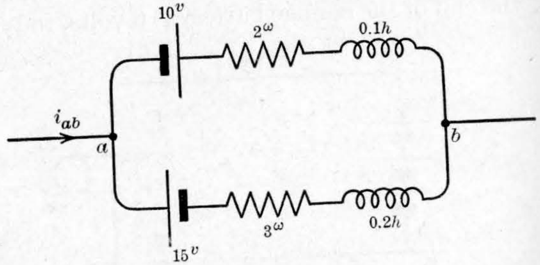


FIG. 253

55. In the parallel connection shown in Fig. 253, at a certain instant the total current (i_{ab}) flowing from a to b is 10 amperes and is increasing at a rate of 500 amperes per second. At the same instant the potential from a to b is -50 volts. Determine the magnitude, direction, and rate of change of the current in each branch.

Ans. Upper branch, $i = 25$ amperes (to right) and $\dfrac{di}{dt} = 100$ amperes per second (increasing). Lower branch, $i = 15$ amperes (to left) and $\dfrac{di}{dt} = 400$ amperes per second (decreasing).

56. The switch connecting the two points, a and b, in Fig. 254 is closed until the current reaches its ultimate value. The switch is then opened, connecting an additional resistance of 2 ohms in series with the circuit. Determine the current flowing in the circuit 0.2 second after the switch is opened.

Ans. 3.38 amperes.

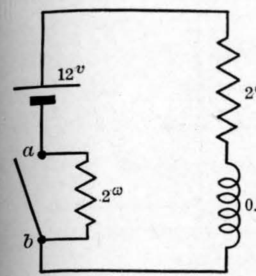


FIG. 254

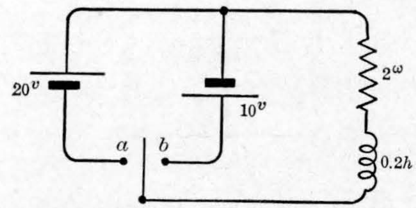


FIG. 255

57. After the switch shown in Fig. 255 is connected to a for 0.1 second, the switch is suddenly thrown to b. Determine (**a**) the current flowing in the coil shown on the right 0.2 second after the switch is thrown to b, and (**b**) the time in seconds after throwing the switch to b when the current in the coil is zero.

Ans. (**a**) 3.47 amperes and (**b**) 0.082 second.

58. When a coil of wire of 2-ohms resistance and 0.1-henry self-inductance is connected to the terminals of a battery of negligible resistance the energy stored in the magnetic field of the coil after the current has reached its ultimate value is 4 joules. How much additional emf must be connected in series with the coil to double the magnetic energy in 0.05 second?

Ans. 11.7 volts.

59. A two-wire transmission line, 1 mile in length, consists of No. 0 stranded copper wires spaced 3 feet on centers. A constant emf of 600 volts is impressed upon the line at the generator end. The load is non-inductive and contains no source of emf. The temperature of the line wires is 25 C. If, after steady operation with a load resistance of 9 ohms, the resistance of the load is suddenly changed from 9 ohms to 4 ohms determine (**a**) the initial emf induced in the transmission line and (**b**) the initial rate of change of the line current.

Ans. (**a**) 298 volts and (**b**) 84,000 amperes per second.

60. A battery of 20 volts emf and negligible resistance is connected across a parallel connection as shown in Fig. 256. How long will it take for the current in the right-hand branch to equal the current in the left-hand branch?

Ans. 0.122 second.

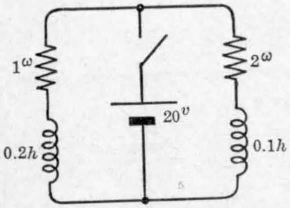


Fig. 256

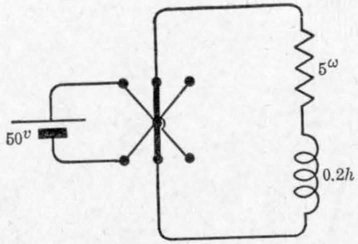


Fig. 257

61. A coil of wire is connected to a battery of 50 volts emf by a reversing switch as shown in Fig. 257. The coil of wire, including the switch and battery, has a resistance of 5 ohms and a self-inductance of 0.2 henry. The switch after being closed until the current has reached its ultimate value is instantaneously reversed. (**a**) How long after the switch is reversed will the current in the coil be zero? (**b**) At what rate will the current be changing at this instant?

Ans. (**a**) 0.0278 second and (**b**) 250 amperes per second.

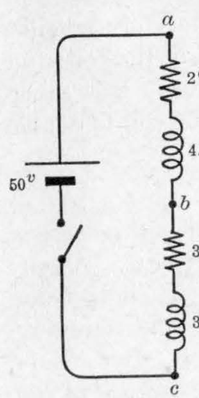


Fig. 258

62. Given the series connection shown in Fig. 258. Neglecting the resistance of the battery, at what time after closing the switch will the power absorbed between *a* and *b* equal the power absorbed between *b* and *c*?

Ans. 0.755 second.

Chapter IV

63. A rectangular coil of 100 turns of wire, 15 inches by 10 inches in dimensions, is rotated about an axis through the centers of the 10-inch sides at a speed of 1000 rpm in a magnetic field of 2000 gausses flux density, the axis of rotation being perpendicular to the flux density. Determine (**a**) the maximum instantaneous

emf generated in the coil and (**b**) the maximum instantaneous torque in pound-feet acting on the coil when conducting two amperes.

Ans. (**a**) 203 volts, and (**b**) 2.86 pound-feet.

64. A two-pole magneto with a drum-wound armature of 1000-ohms resistance between brushes has 1000 armature conductors and an air-gap flux of 36,000 maxwells per pole. If a resistance of 2000 ohms is connected across the terminals of this magneto what speed would be indicated by a terminal potential of 5 volts?

Ans. 1250 rpm.

65. The generator shown in Fig. 41, page 48, has an armature resistance between brushes of 0.1 ohm and a magnetic flux per pole of 6 million maxwells. If a resistance of 0.9 ohm is connected externally between the brushes at what speed must the armature be driven to convert mechanical into electrical energy at a rate of 400 watts?

Ans. 1667 rpm.

66. Referring to the armature winding shown in Fig. 45 (p. 50) determine (**a**) the terminal potential of the dynamo operated as a generator when the magnetic flux per pole is 4 million maxwells, the rotational speed is 1200 rpm and the total armature current is 20 amperes. With the armature at rest and carrying a current of 20 amperes at a temperature of 80 C the potential between the brushes is 2 volts and the potential from each brush to the commutator is 0.5 volt. If the armature winding consists of No. 16 copper wire, (**b**) what is the total length of the wire on the armature?

Ans. (**a**) 20.4 volts, and (**b**) 40.2 feet.

67. A six-pole, 100-kilowatt, shunt generator while operating at full load has a terminal potential of 230 volts. The shunt field resistance is 11 ohms and the armature resistance between brushes is 0.03 ohm. The armature has a lap-winding containing 600 conductors and revolves at a speed of 900 rpm. Determine the magnetic flux per pole.

Ans. 2.71×10^6 maxwells.

68. A six-pole, lap-wound armature has a resistance between terminals, not including brush contact, of 0.0134 ohm at 25 C.

If the armature contains 1200 feet of copper wire determine (**a**) the size of the wire in the American Wire Gage. If each of the 400 conductors on the armature is capable of carrying 20 amperes continuously determine (**b**) the maximum power that may be converted (mechanical to electrical) within the armature when revolving at a speed of 1200 rpm in a magnetic flux per pole of 2 million maxwells.

Ans. (**a**) No. 6 and (**b**) 19.2 kilowatts.

69. A six-pole, wave-wound, direct-current generator is capable of converting mechanical to electrical energy continuously at a rate of 60 kilowatts when operated at a speed of 1200 rpm. If the armature conductors are reconnected to form a lap-winding and the generator is operated at a speed of 1000 rpm, by what per cent must the field flux be increased or decreased (state which) to be capable of converting energy continuously at the same rate as before?

Ans. Increase flux 20 per cent.

70. A shunt generator has the magnetization curve at 1000 rpm shown in Fig. 49, page 56. At what speed must this generator be run at no load to generate an emf of 115 volts with a shunt field resistance of 22.5 ohms?

Ans. 871 rpm.

71. Given the magnetization curve (Fig. 49, page 56) of a 25-kilowatt shunt generator at 1000 rpm. At what speed must this generator be operated to deliver 25 kilowatts at a terminal potential of 120 volts if the armature resistance is 0.03 ohm and the shunt field resistance is 40 ohms? The effect of armature reaction is to be neglected.

Ans. 1191 rpm.

72. The generated emf of a shunt generator when operated at a speed of 1000 rpm at no load is 130 volts. The magnetization curve of this generator is given on page 56. The armature resistance between terminals is 0.03 ohm. If this generator is to be operated with an armature current of 200 amperes, a terminal potential of 130 volts and at the same speed (1000 rpm) how much resistance must be removed from the shunt field circuit? The effect of armature reaction is to be neglected.

Ans. 2.4 ohms.

73. A 25-kilowatt shunt generator (magnetization curve page 56) has a terminal potential of 115 volts at full load and 1000 rpm. Each pole contains 1000 turns, the armature resistance is 0.045 ohm, and the shunt field resistance is 23 ohms. Determine the demagnetizing ampere turns on the armature per pole.

Ans. 500 ampere turns.

74. A shunt generator with an armature resistance of 0.03 ohm and operated at a speed of 1000 rpm has a terminal potential of 115 volts when the armature current is 200 amperes. The magnetization curve of this generator is shown on page 56. Neglecting the effect of armature reaction determine the terminal potential of this generator at no load.

Ans. 125 volts.

75. A shunt generator with a magnetization curve like that shown on page 56 has a terminal potential of 115 volts when operated at no load at 1000 rpm. The armature resistance between brushes is 0.04 ohm. At what speed must the generator be operated to make the terminal potential 120 volts when the load is 20 kilowatts? The effect of armature reaction is to be neglected.

Ans. 1082 rpm.

76. A shunt generator having the magnetization curve shown on page 56 has 2000 turns of wire on each field pole. The armature resistance is 0.05 ohm. When running at 1000 rpm and delivering no load the shunt field current is 4.5 amperes, but when delivering full load of 25 kilowatts the field current has to be increased to 6.0 amperes to keep the terminal potential the same as it was at no load. How many demagnetizing ampere turns per pole are there on the armature at full load?

Ans. 1000 ampere turns.

77. A series generator operated at a speed of 1000 rpm has the same magnetization curve as that shown for a shunt generator on page 56 except that the abscissa represents the series field current and the scale is 100 times that shown (3 amperes being changed to 300 amperes, etc.). If the joint resistance of the armature and series field is 0.025 ohm determine the power output of the

series generator when the resistance of the load is 0.250 ohm and the speed is 1100 rpm.

Ans. 72.5 kilowatts.

78. A 25-kilowatt, 1000-rpm shunt generator (magnetization curve on page 56) has 1800 shunt field turns and the resistance of the shunt field circuit is 30 ohms. A long-shunt compound generator is to be made of this machine by adding 20 series field turns. If there are 3350 demagnetizing ampere turns on the armature at full load what emf will be generated in the armature when the terminal potential of the compound generator is 120 volts and the load is 25 kilowatts?

Ans. 125 volts.

79. A bipolar long-shunt compound generator when operating at full load at 1000 rpm delivers 25 kilowatts at a terminal potential of 115 volts. The magnetization curve of this generator, with its shunt field only excited, is given on page 56. The shunt field has a resistance of 35 ohms and has 1000 turns per pole. The combined resistance of the armature and series field is 0.04 ohm. At full load there are 400 demagnetizing ampere turns per pole on the armature. Determine the nearest integral number of series turns per pole.

Ans. 6 turns per pole.

80. A 25-kilowatt shunt generator with the magnetization curve shown on page 56 has 1000 shunt field turns and when operated at 1000 rpm has a terminal potential of 115 volts at no load. How many series turns must be added to the generator if it is to deliver 25 kilowatts at 115 volts terminal potential under the following simultaneous conditions: (1) the series turns are to be connected to form a long-shunt compound generator; (2) the joint resistance of the armature and the series turns is 0.025 ohm; (3) the demagnetizing ampere turns on the armature at full load are 380 ampere turns.

Ans. 4 turns.

81. Given the following data regarding two shunt generators operating in parallel: No. 1. — generated emf, 118 volts; armature resistance, 0.05 ohm; shunt field resistance, 30 ohms. No. 2. — generated emf, 118.5 volts; armature resistance, 0.03 ohm; shunt field resistance, 20 ohms. Determine the total power delivered by the two generators when the terminal potential is 115 volts.

Ans. 19.2 kilowatts.

82. Two shunt generators, No. 1 and No. 2, are to be operated in parallel. The external characteristics of these generators may be represented by the equations $V_1 = 600 - 0.2\,I_1$ and $V_2 = 580 - 0.1\,I_2$, where V_1 and V_2 represent the terminal potentials and I_1 and I_2 represent the line currents of the respective generators. Each generator can deliver a line current of 300 amperes continuously without overheating. Find (**a**) the line potential when the line currents of the two generators are equal, (**b**) the line current of each generator when the total line current is 300 amperes, (**c**) the maximum power output of the two generators operating in parallel and (**d**) the line potential when no load is connected to the line wires.

Ans. (**a**) 560 volts, (**b**) $I_1 = 166.7$ and $I_2 = 133.3$ amperes, (**c**) 302.5 kilowatts, and (**d**) 586.7 volts.

83. Three shunt generators have the following respective external characteristics: No. 1, $V = 230 - 0.1\,I$; No. 2, $V = 235 - 0.125\,I$; No. 3, $V = 240 - 0.2\,I$. If these three generators are connected in parallel to a lamp load of 0.5-ohm resistance, determine the per cent of the total power supplied to the load by each generator.

Ans. No. 1, 34.4; No. 2, 36.8; No. 3, 28.8 per cent.

84. Two shunt generators, operated in parallel at 1000 rpm, supply power to a lighting load consisting of 120-volt, 60-watt incandescent lamps connected in parallel. The magnetization curve of each generator is the same as that shown on page 56 and each generator has an armature resistance of 0.05 ohm. How many lamps are turned on when the terminal potential of each generator is 120 volts and the shunt field resistances of the two generators are 28 ohms and 26 ohms respectively? Armature reaction and line resistance may be neglected.

Ans. 342 lamps.

85. The armature currents of two shunt generators, A and B, connected in parallel, are 235 amperes and 119 amperes respec-

series generator when the resistance of the load is 0.250 ohm and the speed is 1100 rpm.

Ans. 72.5 kilowatts.

78. A 25-kilowatt, 1000-rpm shunt generator (magnetization curve on page 56) has 1800 shunt field turns and the resistance of the shunt field circuit is 30 ohms. A long-shunt compound generator is to be made of this machine by adding 20 series field turns. If there are 3350 demagnetizing ampere turns on the armature at full load what emf will be generated in the armature when the terminal potential of the compound generator is 120 volts and the load is 25 kilowatts?

Ans. 125 volts.

79. A bipolar long-shunt compound generator when operating at full load at 1000 rpm delivers 25 kilowatts at a terminal potential of 115 volts. The magnetization curve of this generator, with its shunt field only excited, is given on page 56. The shunt field has a resistance of 35 ohms and has 1000 turns per pole. The combined resistance of the armature and series field is 0.04 ohm. At full load there are 400 demagnetizing ampere turns per pole on the armature. Determine the nearest integral number of series turns per pole.

Ans. 6 turns per pole.

80. A 25-kilowatt shunt generator with the magnetization curve shown on page 56 has 1000 shunt field turns and when operated at 1000 rpm has a terminal potential of 115 volts at no load. How many series turns must be added to the generator if it is to deliver 25 kilowatts at 115 volts terminal potential under the following simultaneous conditions: (1) the series turns are to be connected to form a long-shunt compound generator; (2) the joint resistance of the armature and the series turns is 0.025 ohm; (3) the demagnetizing ampere turns on the armature at full load are 380 ampere turns.

Ans. 4 turns.

81. Given the following data regarding two shunt generators operating in parallel: No. 1. — generated emf, 118 volts; armature resistance, 0.05 ohm; shunt field resistance, 30 ohms. No. 2. — generated emf, 118.5 volts; armature resistance, 0.03 ohm; shunt field resistance, 20 ohms. Determine the total power delivered by the two generators when the terminal potential is 115 volts.

Ans. 19.2 kilowatts.

82. Two shunt generators, No. 1 and No. 2, are to be operated in parallel. The external characteristics of these generators may be represented by the equations $V_1 = 600 - 0.2\,I_1$ and $V_2 = 580 - 0.1\,I_2$, where V_1 and V_2 represent the terminal potentials and I_1 and I_2 represent the line currents of the respective generators. Each generator can deliver a line current of 300 amperes continuously without overheating. Find (**a**) the line potential when the line currents of the two generators are equal, (**b**) the line current of each generator when the total line current is 300 amperes, (**c**) the maximum power output of the two generators operating in parallel and (**d**) the line potential when no load is connected to the line wires.

Ans. (a) 560 volts, (b) $I_1 = 166.7$ and $I_2 = 133.3$ amperes, (c) 302.5 kilowatts, and (d) 586.7 volts.

83. Three shunt generators have the following respective external characteristics: No. 1, $V = 230 - 0.1\,I$; No. 2, $V = 235 - 0.125\,I$; No. 3, $V = 240 - 0.2\,I$. If these three generators are connected in parallel to a lamp load of 0.5-ohm resistance, determine the per cent of the total power supplied to the load by each generator.

Ans. No. 1, 34.4; No. 2, 36.8; No. 3, 28.8 per cent.

84. Two shunt generators, operated in parallel at 1000 rpm, supply power to a lighting load consisting of 120-volt, 60-watt incandescent lamps connected in parallel. The magnetization curve of each generator is the same as that shown on page 56 and each generator has an armature resistance of 0.05 ohm. How many lamps are turned on when the terminal potential of each generator is 120 volts and the shunt field resistances of the two generators are 28 ohms and 26 ohms respectively? Armature reaction and line resistance may be neglected.

Ans. 342 lamps.

85. The armature currents of two shunt generators, A and B, connected in parallel, are 235 amperes and 119 amperes respec-

tively and the terminal potential is 115 volts. The magnetization curve of each generator at 1000 rpm is shown on page 56. Generator A has an armature resistance of 0.03 ohm and runs at a speed of 900 rpm; generator B has an armature resistance of 0.05 ohm and runs at a speed of 1000 rpm. Determine the shunt field resistance of each generator.

Ans. Gen. A, 20.9 ohms; Gen. B, 28.1 ohms.

86. Two short-shunt compound generators, A and B, are connected in parallel. The resistances of the shunt and series field circuits are respectively as follows:

	A	B
Shunt field circuit......	50 ohms	20 ohms
Series field circuit......	0.01 ohm.	0.003 ohm.

The potential between the positive and negative busbars is 550 volts and the total current supplied by the two generators is 1500 amperes. Neglecting the resistance of the busbars and the equalizer, if the armature current of generator B is three times that of generator A, find (a) the current in the equalizer and its direction, (b) the armature current of A, and (c) the armature current of B.

Ans. (a) 27.6 amperes (A to B), (b) 384.7 amperes, and (c) 1154.1 amperes.

87. Given the following data regarding a 10-kilowatt, 115-volt bipolar shunt generator: armature speed, 1200 rpm, number of commutator segments, 50; self-inductance of armature winding between two commutator segments, 0.00002 henry; resistance of armature winding between two commutator segments, 0.003 ohm; resistance from armature to a brush located squarely on a commutator segment, 0.002 ohm; shunt field current, 4 amperes. Assuming that the current reverses uniformly determine the emf that must be generated in the armature winding between two commutator segments at full load at the end of the commutation period to produce sparkless commutation.

Ans. 2.14 volts.

88. A shunt motor is connected to the terminals of a shunt generator by two conductors each of 0.1-ohm resistance. The generator armature resistance is 0.3 ohm and the field resistance 50 ohms; the motor armature resistance is 0.2 ohm and the field resistance 55 ohms. If the motor field current is 2 amperes and the motor generated emf is 108 volts find the generated emf of the generator.

Ans. 116.7 volts.

89. A direct-current shunt motor connected to a 230-volt line has an armature resistance of 0.5 ohm. When the armature current is 10 amperes the armature speed is 1200 rpm. What will the armature speed be if the field flux is increased by 10 per cent, a resistance of 1.2 ohms is connected in series with the armature and the armature current is increased to 15 amperes?

Ans. 992 revolutions per minute.

90. A shunt motor, operated on a 220-volt line, runs at a speed of 1200 rpm when its electromagnetic torque is 100 pound-feet, and at a speed of 1230 rpm when its electromagnetic torque is 40 pound-feet. If the line potential is increased to 240 volts the field flux is increased 4 per cent. At what speed would the motor run if operated on a 240-volt line with an electromagnetic torque of 80 pound-feet? The effect of armature reaction may be neglected.

Ans. 1274 rpm.

91. The magnetization curve of a shunt motor is given on page 56. Its armature resistance is 0.077 ohm and its field resistance is 35.4 ohms. Neglecting armature reaction, determine its electromagnetic torque when operated at a speed of 1000 rpm on a 115-volt line.

Ans. 50.3 pound-feet.

92. A shunt generator with the magnetization curve shown on page 56 is operated as a shunt motor on a 115-volt line. The armature resistance is 0.025 ohm and the shunt field resistance is 50 ohms. Determine the speed of the armature when the armature current is 200 amperes.

Ans. 1196 rpm.

93. A direct-current shunt motor when used to drive a pump takes 50 amperes from a 230-volt line. Its armature resistance is 0.2 ohm and the field resistance is 80 ohms. If the rotational

loss is 700 watts, (**a**) how much power is the motor delivering to the pump? (**b**) What current is necessary to drive the motor at no load if the rotational loss is assumed constant?

Ans. (**a**) 9690 watts, and (**b**) 5.9 amperes.

94. The armature current of a shunt motor connected to a 230-volt line and delivering 10 horsepower is 37 amperes. If the armature resistance is 0.36 ohm, what is the rotational loss?

Ans. 557 watts.

95. A direct-current, separately excited motor running at 1500 rpm takes an armature current of 3 amperes from a 115-volt line at no load. Its armature resistance between brushes is 0.5 ohm. If this motor is disconnected from the line and driven by belt at the same speed and the same separate field excitation as before, determine the required mechanical power input (in watts) to the dynamo when a resistance of 10 ohms is connected across its terminals.

Ans. 1567 watts.

96. A shunt motor is loaded by means of a Prony brake and the following data are obtained: line potential, 116 volts; line current, 86.4 amperes; field current, 4.2 amperes; speed, 1220 rpm; balance reading (corrected for zero), 22 pounds; length of brake arm, 2 feet 2 inches; armature resistance, 0.074 ohm. Find (**a**) the rotational loss, and (**b**) the efficiency of the motor at full load.

Ans. (**a**) 770 watts, and (**b**) 82.4 per cent.

97. When a direct-current shunt generator delivers 10 kilowatts at 220 volts terminal potential the efficiency of the generator is 85 per cent. If the shunt field resistance is 90 ohms and the armature resistance is 0.2 ohm, determine the rotational loss of the generator.

Ans. 770 watts.

98. A direct-current shunt motor connected to a 230-volt line has a field resistance of 80 ohms and an armature resistance of 0.2 ohm. The rotational loss of the motor is 600 watts and may be assumed constant. Determine the horsepower output of this motor when it takes 50 amperes from the line.

Ans. 13.1 horsepower.

99. A shunt motor connected to a 230-volt line delivers 10 horsepower at a speed of 1200 rpm. The armature resistance is 0.2 ohm and the rotational loss is 500 watts. Assuming that the rotational loss, armature resistance, field resistance, and line potential remain constant, at what speed will the motor run when the output is 5 horsepower?

Ans. 1216 rpm.

100. When a shunt motor is operated at a speed of 1500 rpm the combined hysteresis and eddy-current loss is 300 watts, of which the hysteresis loss is 40 per cent and the eddy-current loss is 60 per cent. If the field flux is maintained constant what would the combined hysteresis and eddy-current loss be at 1200 rpm?

Ans. 211 watts.

101. A series motor operating on a 230-volt line has a combined armature and series field resistance of 0.4 ohm. What current will this motor take from the line when developing an electromagnetic torque of 60 pound-feet at a speed of 1200 rpm?

Ans. 48.5 amperes.

102. A 15-kilowatt, direct-current shunt generator when operated at full load at 230 volts terminal potential and 1200 rpm has an efficiency of 86 per cent. The shunt field resistance is 60 ohms and the armature resistance is 0.16 ohm. Determine (**a**) the power output and (**b**) the speed of this dynamo when operated as a shunt motor at 230 volts terminal potential and with the same field current and armature current as when operated as a generator at full load. The rotational losses may be assumed constant.

Ans. (**a**) 19.2 horsepower, and (**b**) 1090 rpm.

103. A 25-kilowatt, 220-volt, 800-rpm shunt generator has an armature resistance of 0.12 ohm. When this dynamo is running at no load as a motor at 800 rpm, its armature takes 6.4 amperes from a 220-volt line. Assuming constant rotational loss, what is the efficiency of this dynamo operated as a generator at one-half rated load at 220 volts, if the field resistance is 60 ohms?

Ans. 82.5 per cent.

104. A shunt generator when delivering 15 kilowatts at a terminal potential of 230 volts has an efficiency of 87 per cent. The

shunt field resistance is 65 ohms and the armature resistance 0.15 ohm. The mechanical power input to this generator when driven at the same speed with no generated emf (field disconnected and line switch open) is 300 watts. Determine the combined hysteresis and eddy-current losses of the generator.

Ans. 418 watts.

105. A 230-volt, 15-kilowatt shunt generator with a shunt field resistance of 100 ohms and an armature resistance of 0.23 ohm operates at full load at an efficiency of 87 per cent. Assuming no change in the rotational losses or air-gap flux determine the per cent change in speed from no load to full load when this dynamo is operated on a 230-volt line as a shunt motor.

Ans. Decreases 6.5 per cent.

106. A belt-driven 15-kilowatt shunt generator when operated at full load at 230 volts terminal potential and 1500 rpm has an efficiency of 85 per cent. The shunt field resistance is 58 ohms and the armature resistance is 0.18 ohm. If the belt should slip off while this generator is operating in parallel with other generators on a 230-volt line at what speed would it operate, assuming that the rotational loss is directly proportional to the speed? The effect of armature reaction may be neglected.

Ans. 1420 rpm.

107. A 230-volt, 15-kilowatt shunt generator with a shunt field resistance of 90 ohms and an armature resistance of 0.2 ohm operates at full load at an efficiency of 87 per cent. Assuming no change in the rotational losses or air-gap flux determine the efficiency of this dynamo when operated as a motor at full load.

Ans. 86.2 per cent.

108. When connected to a 230-volt line a shunt motor with a field resistance of 80 ohms and an armature resistance of 0.2 ohm takes 5 amperes from the line at no load. Assuming the rotational losses to be constant determine the maximum efficiency at which this motor will operate.

Ans. 87.3 per cent.

109. A 230-volt, 15-horsepower shunt motor has an efficiency of 85 per cent at full load. Its armature resistance is 0.25 ohm and its field resistance is 80 ohms. Determine the resistance of a starting box which will limit the initial starting current of the motor to the full load value.

Ans. 4 ohms.

110. A series motor having a combined armature and series field resistance of 0.1 ohm runs at a speed of 1000 rpm when taking 100 amperes from a 230-volt line. At what speed would this motor run when developing the same torque as before if it were connected to a 115-volt line?

Ans. 477 rpm.

111. A shunt motor with a field resistance of 35.4 ohms and an armature resistance of 0.025 ohm is operated on a 115-volt line and delivers 28 horsepower at a speed of 1000 rpm. Its magnetization curve is given on page 56. Determine its rotational loss.

Ans. 1100 watts.

112. A shunt motor with a terminal potential of 230 volts and an armature resistance of 0.3 ohm takes an armature current of 40 amperes when operated at a speed of 1500 rpm. If the speed is reduced to 1200 rpm by connecting a resistance of 0.7 ohm in series with the armature determine the percentage change in the electromagnetic torque. The terminal potential and field resistance remain unchanged throughout.

Ans. Increases 39 per cent.

113. A shunt motor has a shunt field resistance of 28.7 ohms and an armature resistance of 0.04 ohm. Its magnetization curve at 1000 rpm is shown on page 56 and its rotational loss (to be assumed constant) is 1000 watts. Determine the pulley torque of this motor when connected to a 115-volt line and with a total power input of 20 kilowatts.

Ans. 135 pound-feet.

114. The armature of a four-pole, lap-wound shunt motor contains 420 conductors and has a resistance of 0.17 ohm between terminals. The flux per pole when connected to a 115-volt line is 1 million maxwells. This motor is to be direct-connected to a ventilating fan which has a torque-speed characteristic represented by $T = 7 \times 10^{-6}S^2$; torque in pound-feet and speed in

rpm. Neglecting the reactive torque of the motor due to the rotational losses, determine the speed at which this motor will drive the fan when the motor is connected to a 115-volt line.

Ans. 1550 rpm.

115. A 230-volt shunt motor takes an armature current of 3.16 amperes at no load with the generated emf and speed adjusted to be the same as at full load. If the armature resistance is 0.518 ohm and the armature current is 28.9 amperes at full load determine the horsepower rating of the motor.

Ans. 7.36 horsepower.

116. A shunt motor with a field resistance of 250 ohms and an armature resistance of 0.2 ohm is direct-connected mechanically to a long-shunt compound generator with a shunt field resistance of 52 ohms, a series field resistance of 0.008 ohm and an armature resistance of 0.04 ohm. With no load on the generator and the shunt motor connected to a 550-volt line the input to the motor is 5.3 kilowatts and the terminal potential of the generator is 240 volts. With the generator disconnected mechanically from the motor the input to the motor is 2.8 kilowatts. Assuming the rotational losses to be constant, determine the rotational loss of the motor and the generator respectively.

Ans. Motor, 1588 watts; generator, 1384 watts.

Chapter V

117. A direct-current milliammeter gives a full-scale deflection when the current in the moving coil is 0.025 ampere. The resistance of the moving coil is 3 ohms. (**a**) What resistance must be connected in parallel with the moving coil so that a full-scale deflection will indicate 50 amperes in the circuit in which the instrument is connected? (**b**) What resistance must be connected in series with the moving coil (without the shunt) so that full-scale deflection will indicate 150 volts? (**c**) At what point on the series resistance should a terminal be connected so that full-scale deflection will indicate 15 volts? (**d**) If the voltmeter constructed in accordance with the requirements stated under question (**b**) is connected in series with an unknown resistance across a 115-volt line and the voltmeter reads 12 volts, what is the value of the unknown resistance?

Ans. (**a**) 0.001501 ohm, (**b**) 5997 ohms, (**c**) 597 ohms (from moving coil), and (**d**) 51,500 ohms.

118. A 150-volt voltmeter of 15,000 ohms total resistance contains a 15-volt tap and gives full-scale deflection when 15 volts is impressed between the 15-volt tap and the negative terminal. What additional resistance should be connected in parallel between the 15-volt tap and the negative terminal so that the voltmeter will give full-scale deflection when an emf of 300 volts is impressed between the 150-volt terminal and the negative terminal?

Ans. 1350 ohms.

119. A 150-volt voltmeter has a normal resistance of 15,000 ohms. A part of its non-inductive resistance becomes short-circuited so that its resistance between terminals is 14,500 ohms. When the voltmeter reads 115 volts (**a**) what is the actual potential between its terminals? A 1.5-volt potentiometer is used to calibrate a 15-ampere ammeter. (**b**) What size of standard resistance should be connected between *m* and *n* in Fig. 98, page 96?

Ans. (**a**) 111.1 volts and (**b**) 0.1 ohm.

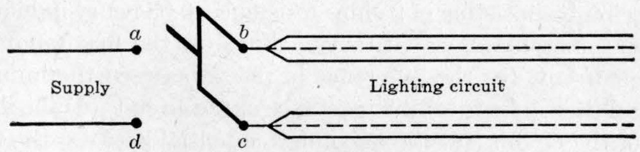


FIG. 259

120. In the two-wire direct-current lighting circuit shown in Fig. 259 a 15,000-ohm voltmeter connected between *a* and *d* reads 115 volts. With the switch open, all lamps turned off, and a short circuit between *a* and *b* the same voltmeter connected between *c* and *d* reads 5 volts. Determine the insulation resistance between the two wires of the lighting circuit.

Ans. 0.33 megohm.

121. A transmission line 5 miles in length is grounded at an unknown point (G_2). The far ends of the line are connected and a battery, two adjustable resistances, and a galvanometer are connected to the near ends as shown in Fig. 260, one terminal of the battery being grounded. The galvanometer shows no

deflection when R_1 equals 700 ohms and R_2 equals 200 ohms. Determine the distance, d, to the ground on the line.

Ans. 2.22 miles.

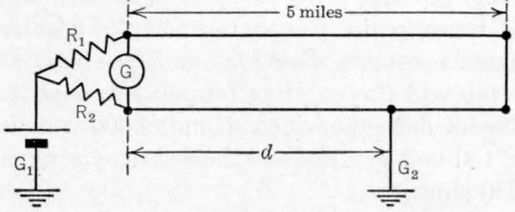


FIG. 260

Chapter VI

122. An emf, $e_{ab} = 60 \sin 377\,t$, is connected in series with an emf, $e_{bc} = 50 \sin (377\,t + 30°)$, and an emf, $e_{cd} = 80 \sin (377\,t - 45°)$. Determine the resultant emf, e_{ad}.

Ans. $e_{ad} = 163 \sin (377\,t - 11.2°)$.

123. An alternating emf, $e = 150 \sin 377\,t$, is impressed upon a series circuit consisting of 2 ohms resistance, 0.03 henry inductance, and 500 microfarads capacitance. Find (**a**) the maximum value of the current, (**b**) the difference in phase between the impressed emf and the current, (**c**) the reactance of the circuit, (**d**) the impedance of the circuit, (**e**) the maximum potential between the terminals of the condenser, (**f**) the maximum potential between the terminals of the resistance and inductance combined, (**g**) the frequency of the current and (**h**) the capacitance to be connected in series with the 500 microfarads capacitance to produce resonance.

Ans. (**a**) 23.7 amperes, (**b**) 71.6°, (**c**) 6 ohms, (**d**) 6.33 ohms, (**e**) 125.6 volts, (**f**) 272 volts, (**g**) 60 cycles per second, and (**h**) 444 mfs.

124. An alternating emf, $e = 300 \sin 157\,t$, is impressed upon a coil of wire and a condenser connected in series. The coil of wire has a resistance of 5 ohms and a self-inductance of 0.03 henry. The condenser has a capacitance of 800 microfarads. Determine (**a**) the equation for the instantaneous potential between the terminals of the coil of wire referred to the impressed emf as the axis of reference, and (**b**) the maximum rate at which energy is supplied to the condenser.

Ans. (**a**) $v = 346 \sin (157\,t + 76.3°)$, and (**b**) 10.1 kilowatts.

125. At a frequency of 60 cycles per second a series connection containing resistance, inductance, and capacitance is in resonance and has an impedance of 5 ohms. At a frequency of 25 cycles per second the same connection has an impedance of 10 ohms. Determine (**a**) the resistance, (**b**) the inductance, and (**c**) the capacitance respectively of the series connection.

Ans. (**a**) 5 ohms, (**b**) 0.0115 henry, and (**c**) 608 microfarads.

126. The impedance of a coil of wire when connected to a 60-cycle generator is 10 ohms and the power factor is 0.8. Determine (**a**) the impedance and (**b**) the power factor of the same coil of wire when connected to a 25-cycle generator.

Ans. (**a**) 8.36 ohms and (**b**) 0.956.

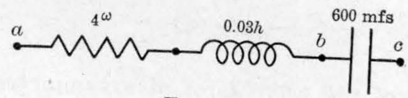


FIG. 261

127. Determine the maximum value of a 60-cycle sinusoidal emf that must be impressed between a and c in Fig. 261 to make the maximum instantaneous power absorbed between a and b 2 kilowatts.

Ans. 126 volts.

128. A continuous series connection of 0.0004-henry inductance and 0.0005-microfarad capacitance is to be tuned for resonance at a frequency of 600 kilocycles per second by the addition of a suitable condenser. Determine whether this additional condenser should be connected in series or in parallel with the existing condenser, and determine the capacitance required.

Ans. 0.000271 microfarad in series.

129. When an emf, $e = 100 \sin 377\,t$, is impressed upon a transmission line the current established in the line is $i = 10 \sin (377\,t - 45°)$. Determine the ratio of the energy, returned to the source of emf, to the energy delivered from the source of emf, during one cycle.

Ans. 0.0639.

130. The maximum value of an isosceles triangular-shaped alternating-current wave is 10 amperes. What is its effective value?

Ans. 5.78 amperes.

131. Each half of the wave form of an alternating current is semicircular in shape and its maximum value is 10 amperes. Determine its effective value.

Ans. 8.16 amperes.

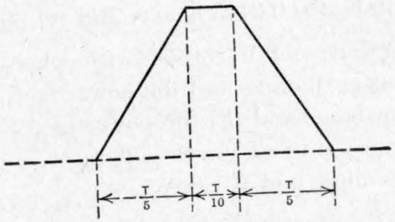


FIG. 262

132. One-half of the wave form of a symmetrical alternating emf is shown in Fig. 262. The maximum value of the emf is 100 volts. Determine its effective value.

Ans. 68.3 volts.

133. A series alternating-current circuit contains three parts, A, B, and C. A has a resistance of 2 ohms and an inductance of 0.01 henry, B has a resistance of 3 ohms and a capacitance of 1000 microfarads, and C has a capacitance of 200 microfarads. If a 60-cycle alternating emf of 230 volts (effective value) is impressed upon this series circuit, determine (**a**) the effective current, (**b**) the power factor of B, and (**c**) the effective potential across part B.

Ans. (**a**) 17.5 amperes, (**b**) 0.75, and (**c**) 70 volts.

134. An alternating emf of 230 volts (effective value) is impressed upon a circuit containing two sections, A and B, connected in series. Section A has a resistance of 3 ohms and an inductive reactance of 6 ohms; section B has a resistance of 2 ohms and a capacitive reactance of 4 ohms. Find (**a**) the effective value of the current, (**b**) the effective potentials across sections

A and B respectively, (**c**) the power supplied to sections A and B respectively, and (**d**) the power factor of the circuit.

Ans. (**a**) 42.7 amperes, (**b**) 286 volts across A and 191 volts across B, (**c**) 5460 watts to A and 3640 watts to B, and (**d**) 0.928.

135. When a series connection containing a 3-ohm resistance and a condenser of unknown capacitance is connected across a 115-volt 60 cps, the potential across the condenser is 60 volts. What would the potential across the condenser be if this series connection were connected across a 115-volt 25-cycle line?

Ans. 94.8 volts.

136. A coil of wire when connected to a 230-volt 60 cps source of power takes 1000 watts at 0.8 power factor (lagging current). At what frequency will this same coil of wire take 500 watts from a 230-volt source of power?

Ans. 116.5 cycles per second.

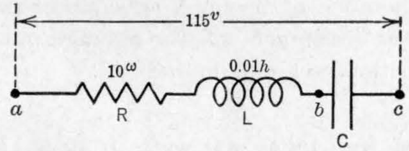


FIG. 263

137. A sinusoidal emf of 115 volts (effective value) and 60 cps frequency is impressed upon the series connection shown in Fig. 263. The condenser between b and c is adjusted until the effective potential from b to c is twice the effective potential from a to b. Determine (**a**) the effective potential from a to b, (**b**) the maximum instantaneous power supplied to the condenser, and (**c**) the average power supplied to the entire connection from a to c.

Ans. (**a**) 60.6 volts, (**b**) 689 watts, and (**c**) 323 watts.

138. When a 230-volt (effective value) sinusoidal emf is applied to a series connection the maximum instantaneous rate at which energy is being delivered to the circuit is 5000 watts, while the maximum instantaneous rate at which energy is being returned to the source of power is 500 watts. Determine (**a**) the power factor and (**b**) the impedance of the series connection.

Ans. (**a**) 0.818 and (**b**) 19.2 ohms.

139. A 60-cycle sinusoidal emf of 115 volts (effective value) is impressed upon a series connection of 6 ohms resistance, 4 ohms inductive reactance, and a variable capacitance. For what value of the capacitance will the potential between the terminals of the condenser be a maximum?

Ans. 204 microfarads.

140. When a sinusoidal emf of 115 volts (effective value) and 60 cycles per second frequency is impressed upon a coil of wire the maximum instantaneous power and the average power supplied to the coil of wire are 25 kilowatts and 10 kilowatts respectively. Determine (**a**) the resistance and (**b**) the inductance of the coil of wire.

Ans. (**a**) 0.588 ohm and (**b**) 0.00174 henry.

141. A sinusoidal emf of 115 volts (effective value) is impressed upon a variable resistance, an inductive reactance of 8 ohms, and a capacitive reactance of 2 ohms, all connected in series. For what value of the resistance will the average power absorbed by the series connection be a maximum?

Ans. 6 ohms.

142. A coil of wire takes 400 watts from a 115-volt, 60-cycle line and takes 1350 watts from a 115-volt, 25-cps line. Determine (**a**) the resistance, and (**b**) the self-inductance of the coil of wire.

Ans. (**a**) 4.9 ohms and (**b**) 0.0312 henry.

143. Two impedances, A and B, are connected in parallel. A has a resistance of 2 ohms and an inductive reactance at 60 cps of 5 ohms. B has a resistance of 4 ohms and a capacitive reactance at 60 cps of 3 ohms. Find the equivalent resistance of this parallel connection (**a**) to a 60-cps alternating current, and (**b**) to a direct current.

Ans. (**a**) 4.15 ohms, and (**b**) 2 ohms.

144. An impedance coil of 5 ohms resistance and 0.08 henry inductance is connected in parallel with a condenser of 60 microfarads capacitance. What is the power factor of this parallel connection (**a**) at 60 cycles per second, and (**b**) at 25 cycles per second?

Ans. (**a**) 0.483, and (**b**) 0.418.

145. What resistance should be connected in parallel with a condenser of 100 microfarads capacitance to make the capacitance of the equivalent series connection 120 microfarads at a frequency of 60 cycles per second?

Ans. 59.3 ohms.

146. The impedances of two coils, A and B, are each 10 ohms at 60 cycles per second. At 25 cycles per second the impedance of A is 5.38 ohms and the impedance of B is 8.67 ohms. Find the joint impedance of A and B at 60 cycles when connected (**a**) in parallel, and (**b**) in series.

Ans. (**a**) 5.24 ohms, and (**b**) 19.1 ohms.

147. A parallel connection consists of two branches, A and B. A has a resistance of 3 ohms and an inductive reactance of 5 ohms. B has a resistance of 2 ohms and a capacitive reactance of 4 ohms. If the total current taken by the parallel connection is 12 amperes find the current in each branch.

Ans. I_A equals 10.5 amperes and I_B equals 13.7 amperes.

148. In a parallel connection containing two branches one branch has a resistance of 3 ohms and an inductive reactance of 4 ohms, and the other branch contains an adjustable resistance connected in series with a capacitive reactance of 5 ohms. For what value should the resistance be adjusted to make the power factor of the parallel connection unity?

Ans. 2.5 ohms.

149. Two coils of wire, A and B, are connected in parallel. Coil A has a resistance of 6 ohms and a self-inductance of 0.02 henry. Coil B has a resistance of 4 ohms and a self-inductance of 0.01 henry. Determine the resultant self-inductance of this parallel connection at a frequency of 60 cycles per second.

Ans. 0.00673 henry.

150. Given the parallel connection with respective resistances and capacitive reactances at 60 cycles per second frequency as indicated in Fig. 264. If a 60-cycle sinusoidal emf of 115 volts effective value is impressed between a and b determine the effective value of the potential between c and d.

Ans. 110.4 volts.

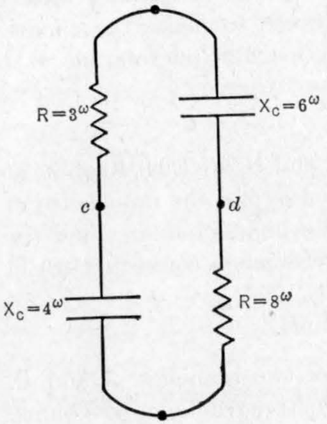


FIG. 264

151. An impedance A is connected in series with two impedances B and C, connected in parallel. The resistances of A, B, and C are 4, 2, and 5 ohms respectively, and the reactances are +3, +6, and −7 ohms respectively. If an emf of 230 volts is impressed upon this circuit, find the current in A, B, and C respectively.

Ans. I_A equals 18.2 amperes, I_B equals 22.1 amperes, and I_C equals 16.3 amperes.

152. Given the parallel connection shown in Fig. 265 by what per cent will the impedance from a to b be changed when the switch at c is closed?

Ans. Increases 76 per cent.

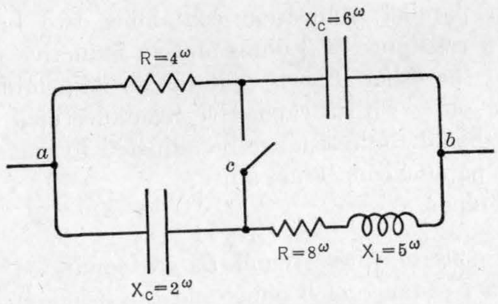


FIG. 265

153. Determine the effective value of a 25-cps sinusoidal emf that must be impressed between a and c in Fig. 266 to make the effective value of the current in the 600-microfarad condenser 5 amperes.

Ans. 49.2 volts.

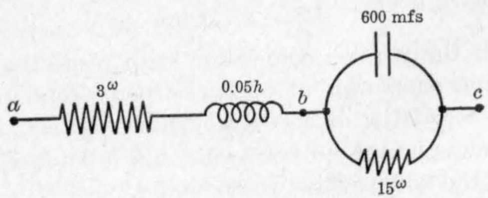


FIG. 266

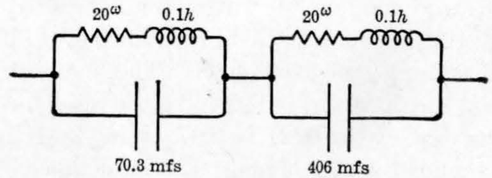


FIG. 267

154. Given the series-parallel connection shown in Fig. 267, determine the current taken by this connection when connected across a 230-volt 60-cps line.

Ans. 2.71 amperes.

Chapter VII

155. The power supplied to a coil of wire is measured with an electrodynamometer wattmeter connected as shown in Fig. 130, page 122. The potential coil connection of the wattmeter has a resistance of 2000 ohms and the current coil has a resistance of 0.1 ohm. The inductance of each wattmeter coil is negligible. With the coil of wire connected between the line wires at the right of the figure the wattmeter reads (correctly) 150 watts, the current in the current coil is 4.0 amperes, and the current in the potential coil is 0.06 ampere. Determine the reactance of the coil of wire.

Ans. 28.4 ohms.

156. The power supplied to an alternating-current load is measured with an electrodynamometer wattmeter connected as shown in Fig. 130,page 122. The load, which is connected on the right side of the figure, consists of resistance and inductance only, and the frequency is 60 cps. The potential coil connection of the wattmeter has a resistance of 2000 ohms and the current coil has a resistance of 0.1 ohm. The inductance of each wattmeter connection is negligible. The wattmeter reads (correctly) 150 watts, the current in the potential coil is 0.06 ampere, and the current in the current coil is 4.0 amperes. Determine (**a**) the

actual power delivered to the load, (b) the resistance of the load, and (c) the inductance of the load.

Ans. (a) 148.4 watts, (b) 9.28 ohms, and (c) 0.0755 henry.

157. An electrodynamometer wattmeter, connected as shown in Fig. 130, page 122, has a current coil resistance of 0.133 ohm and a potential coil resistance of 3160 ohms. The line potential (in the place shown on the diagram) is 115 volts, the resistance of the load (not including the wattmeter) is 2.17 ohms, and the inductive reactance of the load is 22.9 ohms. The inductance of each wattmeter coil is negligible and the wattmeter readings require no correction. Determine (a) the wattmeter reading, (b) the actual power supplied to the load, and (c) the power consumed by the wattmeter in measuring this power.

Ans. (a) 57.3 watts, (b) 54.0 watts, and (c) 7.49 watts.

158. When the electrodynamometer wattmeter shown in Fig. 130, page 122 is connected (at the right) to a load containing no reactance and (at the left) to a 115-volt (effective value) line the wattmeter reads (correctly) 13.2 watts. The potential coil of the wattmeter has a resistance of 2000 ohms, the current coil a resistance of 0.1 ohm, and both coils have a negligible inductance. What will the wattmeter read if the potential coil terminal is transferred from the left-hand terminal of the current coil to the right-hand terminal, all other connections remaining the same?

Ans. 19.8 watts.

Chapter VIII

159. A three-phase, Y-connected alternator delivers 400 kilowatts at 0.9 power factor to a balanced inductive load. If the terminal potential of the alternator is 2300 volts find (a) the line current, (b) the phase current, (c) the phase angle between the line current (*aa′*) and the line potential (*ba*), (d) the phase angle between the phase current (*oa*) and the phase potential (*oa*), and (e) the output of the alternator in kilovolt-amperes. The terminal notation applies to Fig. 145, page 132.

Ans. (a) 111.5 amperes, (b) 111.5 amperes, (c) 55.8°, (d) 25.8°, and (e) 444.4 kva.

160. A three-phase, Δ-connected alternator delivers 400 kilowatts at 0.9 power factor to a balanced inductive load. If the terminal potential of the alternator is 2300 volts, find (a) the line current, (b) the phase current, (c) the phase angle between the line current (*aa′*) and the line potential (*ba*), (d) the phase angle between the phase current (*bc*) and the phase potential (*bc*), and (e) the output of the alternator in kilovolt-amperes. The terminal notation applies to Fig. 147, page 133.

Ans. (a) 111.5 amperes, (b) 64.4 amperes, (c) 55.8°, (d) 25.8°, and (e) 444.4 kva.

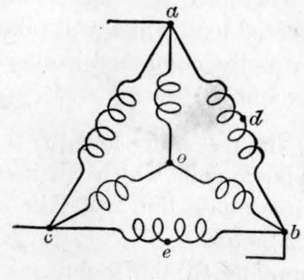


FIG. 268

161. A balanced Y-connected and a Δ-connected load are connected in parallel as shown in Fig. 268. If the line potential is 2300 volts, determine the potential (a) between *o* and *d*, (b) between *d* and *e*, and (c) between *e* and *a*. The points *d* and *e* are located midway between *a* and *b*, and *b* and *c*, respectively.

Ans. (a) 664 volts, (b) 1150 volts, and (c) 1992 volts.

162. A Y-connected and a Δ-connected load are connected in parallel to a three-phase transmission line. The phase current in each load is 10 amperes; the power factor of the Y-connected load is unity and the power factor of the Δ-connected load is 0.5 (lagging current). Find (a) the line current, and (b) the power factor of the combined loads.

Ans. (a) 24 amperes, and (b) 0.778.

163. Three impedances, each having a resistance of 6 ohms and a reactance of 4 ohms, are connected in Y to a three-phase source of power. Determine (a) the resistance and (b) the reactance of three impedances which, when connected in Δ to the same three-phase source of power in place of the Y-connected load, will

take the same power at the same power factor as the Y-connected load.

Ans. (**a**) 18 ohms and (**b**) 12 ohms.

164. A balanced, Y-connected load and a balanced Δ-connected load are connected in parallel to a three-phase transmission line. The Y-connected load takes 16 kilowatts at a power factor of 0.8 (leading current) and the Δ-connected load takes 9 kilowatts at a power factor of 0.6 (lagging current). The line potential is 2300 volts. Find (**a**) the resistance per phase and (**b**) the reactance per phase of a Y-connected load which will take the same power at the same power factor as the combined loads above.

Ans. (**a**) 212 ohms and (**b**) zero.

165. Determine (**a**) the resistance and (**b**) the reactance of each of three similar impedance coils which when connected in Y to a balanced 230-volt, three-phase line will take a total power of 20 kilowatts at 0.4 power factor.

Ans. (**a**) 0.423 ohm, and (**b**) 0.970 ohm.

166. The current coil of a single wattmeter is connected in line aa' of a balanced three-phase load which takes 80 kilowatts at a power factor of 0.8 (lagging current). What will this wattmeter read when its potential coil is connected (**a**) between line aa' and line bb', (**b**) between line aa' and line cc', and (**c**) between line bb' and line cc'?

Ans. (**a**) 22,650 watts, (**b**) 57,300 watts, and (**c**) 34,700 watts.

167. The current coil of a wattmeter is connected in series with one line wire aa' of a three-phase transmission line. If the potential coil is connected between line aa' and line cc' the wattmeter reads 9 kilowatts and when the potential coil is connected between line bb' and line cc' the wattmeter reads 4 kilowatts. Determine the total power transmitted to a balanced inductive load.

Ans. 14 kilowatts.

168. The power supplied to a three-phase induction motor is measured by two wattmeters which read 9 and 5 kilowatts respectively. If the line potential is 550 volts how much current does the motor take from the line?

Ans. 16.4 amperes.

169. Two wattmeters are connected to a balanced Y-connected three-phase load as shown in Fig. 157, page 138. Wattmeter No. 1 reads +6000 watts and wattmeter No. 2 reads +4000 watts. If the potential coil connection to line c becomes broken, leaving the potential coils connected in series between line a and line b, what will each wattmeter read?

Ans. $P_1 = +2000$ watts and $P_2 = +3000$ watts.

170. A three-phase, 60-kilovolt-ampere, synchronous generator, while operating at full load, delivers 54 kilowatts to a balanced inductive load connected to its terminals. If the power supplied to the load is measured by the two-wattmeter method what will each wattmeter read?

Ans. P_1 reads +34.6 kilowatts and P_2, +19.4 kilowatts.

171. Three condensers, each of 100 microfarads capacitance, are connected in Δ to a three-phase, 230-volt 60-cps generator. The power supplied to the condensers is measured by the two-wattmeter method. What will each wattmeter read?

Ans. P_1 reads −1730 watts and P_2, +1730 watts.

172. The power supplied to a Δ-connected load is measured by three wattmeters connected as shown in Fig. 156, page 137. Each wattmeter reads 50 kilowatts and the power factor of the load is 0.8 (lagging current). If the potential coil of wattmeter No. 3 burns out what will each of the other two wattmeters read?

Ans. P_1 reads 53.8 kilowatts, and P_2 reads 21.2 kilowatts.

173. The two wattmeters, P_1 and P_2, in Fig. 157, page 138, read +26.7 kilowatts and +17.3 kilowatts respectively. What will each wattmeter read if an open circuit occurs between o and a?

Ans. P_1 reads zero and P_2, 22.0 kilowatts.

174. A three-phase, Y-connected load of 3 ohms resistance and 4 ohms capacitive reactance per phase is connected to a three-phase, 230-volt line. If the power input to this load is measured by the two-wattmeter method what will each wattmeter read?

Ans. 732 watts and 5610 watts.

Chapter IX

175. A substation receives 2000 kilowatts at 25 cycles from a generating station, 12 miles distant, over a three-phase line formed

of three No. 0 copper wires. The resistance of each wire per mile is 0.539 ohm and the inductance of each wire per mile is 1.69 millihenrys. A line potential of 13,000 volts is maintained at the substation and the power factor of the load connected to the substation is 0.9 (lagging current). Assuming a balanced system determine (**a**) the line potential at the generating station, (**b**) the power lost in the transmission line, and (**c**) the power factor at the generating station.

Ans. (**a**) 14,250 volts, (**b**) 188 kilowatts, and (**c**) 0.899.

176. A three-phase synchronous generator supplies 600 kilowatts to a three-phase synchronous motor at a power factor of 0.9 (leading current). The resistance and reactance (inductive) of each transmission line wire are 0.5 and 0.8 ohm respectively. Determine the line potential at the generator when the line potential at the motor is 2300 volts.

Ans. 2350 volts.

177. The line potentials at the load and generator ends of a single-phase transmission line are each 6600 volts. The resistance of the line (both wires) is 6 ohms and the inductive reactance of the line (both wires) is 8 ohms. If the power factor at the load end of the line is 0.752 what is the line current?

Ans. 99 amperes.

178. A 4400-volt three-phase power station delivers 500 kilowatts to a Δ-connected three-phase load. The resistance of each line wire of the transmission line is 4 ohms and the current in each phase of the load is 50 amperes. What is the power factor at the power station?

Ans. 0.893.

179. A 230-volt three-phase induction motor is connected to a switchboard by copper wires, each of 0.1 ohm resistance and 0.05 ohm inductive reactance. What line potential must be maintained at the switchboard when the motor input is 15 kilowatts at rated potential and 0.8 power factor (lagging current)?

Ans. 239 volts.

180. A three-phase transmission line is to be constructed which will transmit power a distance of 15 miles to a factory which takes 500 kilowatts at a line potential of 13,200 volts and at 0.8 power factor (lagging current). If the efficiency of transmission is to be 85 per cent determine the required size (A.W.G.) of the copper line wires at 30 C.

Ans. No. 6.

181. When a synchronous generator supplies 2500 kilowatts to a three-phase transmission line, 14 miles in length, the line potential at the load is 13,000 volts, the power factor at the load is 0.85 (lagging current) and the efficiency of transmission is 0.9. Determine the nearest size (A.W.G.) of the aluminum line wires at 30 C.

Ans. No. 0000.

182. Power is transmitted over a three-phase transmission line to a balanced inductive load where the line potential is 2300 volts. Each wire has a resistance of 1.5 ohms and an inductive reactance of 3.0 ohms. The power at each end of the line is measured by the two-wattmeter method. At the load end one wattmeter reads +330 kilowatts and the other reads +130 kilowatts. What would each wattmeter at the generator end read?

Ans. P_1 reads +431 kilowatts and P_2 reads +123 kilowatts.

183. The power at the generator and at the load end of a three-phase transmission line is measured by the two-wattmeter method. At the generator end the two wattmeters read +78 kilowatts and +40 kilowatts, respectively, and the line potential is 2500 volts. At the load end the two wattmeters read +65 kilowatts and +35 kilowatts respectively. Assuming a balanced load and negligible capacitive reactance in the transmission line determine (**a**) the resistance and (**b**) the reactance of each transmission line wire.

Ans. (**a**) 6.16 ohms and (**b**) 4.68 ohms.

184. A three-phase generator is connected to a three-phase motor by three lines, each having a resistance of 0.012 ohm and inductive reactance of 0.016 ohm. Determine (**a**) the line potential, (**b**) the power input, and (**c**) the power factor at the motor when the generator output is 20,000 kilowatts at 2400 volts and 0.85 power factor (lagging current).

Ans. (**a**) 2220 volts, (**b**) 18,850 kilowatts, and (**c**) 0.865.

Chapter X

185. A three-phase, Y-connected, synchronous generator supplies power to a balanced load at a line potential of 230 volts at the generator. The power is measured by the two-wattmeter method and each wattmeter reads 10 kilowatts. If the resistance and reactance of each phase of the armature is 0.1 ohm and 0.3 ohm respectively find the generated emf per phase of the generator.

Ans. 138.7 volts.

186. If one phase of a three-phase, Δ-connected, 100-kilovolt-ampere synchronous generator is burnt out, how much power may each of the remaining phases supply to a balanced three-phase load of 0.8 power factor (lagging current)?

Ans. 33.1 and 13.1 kilowatts.

187. A 500-kilovolt-ampere, 2300-volt, three-phase synchronous generator supplies 400 kilowatts to an inductive load at 0.95 power factor. If a non-inductive (unity power factor) lighting load is to be connected in parallel with the above load determine the maximum power that may be supplied to the lighting load without exceeding the rated capacity of the synchronous generator.

Ans. 82.5 kilowatts.

188. A two-pole, Δ-connected, three-phase 25-cycle, synchronous turbo-generator has a total rotational loss of 10 kilowatts and an armature resistance per phase of 1.5 ohms. What driving torque (in pound-feet) must be supplied by a steam turbine when the generator is delivering 300 kilowatts at 2300 volts terminal potential and 0.8 power factor (lagging current)?

Ans. 1520 pound-feet.

189. A Δ-connected, three-phase generator with a phase resistance of 9 ohms and a phase inductive reactance of 12 ohms is connected to a transmission line of 3.5 ohms resistance and 7 ohms inductive reactance per line wire. If the line potential at the load is to be 2300 volts at no load and also with a load of 100 kilowatts, 0.85 power factor (lagging current) by what per cent must an automatic regulator in the power house increase the emf of the generator?

Ans. 26 per cent.

190. Two three-phase synchronous generators operating in parallel deliver power at a line potential of 500 volts to an inductive load of 100 kilowatts at 0.8 power factor. If the armature currents of the two generators are equal and one alternator is operating at unity power factor how much power does each alternator supply to the load?

Ans. 78.5 and 21.5 kilowatts.

191. Two three-phase synchronous generators, A and B, connected in parallel supply 50 kilowatts to an inductive load at 0.9 power factor. If A supplies one-third of this load at 0.8 power factor what is the power factor of B if the phase current lags the phase potential in each alternator?

Ans. 0.943.

Chapter XI

192. One hundred kilowatts are supplied to a 2300-volt, three-phase, Δ-connected synchronous motor at 0.8 power factor (leading current). The resistance and reactance of each phase of the motor are 8 ohms and 10 ohms respectively. Determine the generated emf of the motor per phase.

Ans. 2305 volts.

193. How much power will a Y-connected synchronous motor take from a 230-volt, three-phase transmission line at 0.8 power factor (leading current) if the armature resistance per phase is 0.5 ohm, the armature reactance per phase is 0.6 ohm, and the generated emf of the motor is equal to the terminal potential?

Ans. 5.54 kilowatts.

194. A 2300-volt, three-phase industrial power plant of 1000 kilovolt-amperes capacity supplies 900 kilowatts to an induction motor load at 0.9 power factor (lagging current). An extension to the factory involves the installation of an additional 120 horsepower motor. It is proposed to install a synchronous motor of 89.5 per cent (alternating current) efficiency (at full load) with its field adjusted to make the power factor of the combined load unity. Determine (**a**) the input rating of the synchronous motor in kilovolt-amperes, and (**b**) the power factor at which it must operate.

Ans. (**a**) 447 kva., and (**b**) 0.224.

195. A three-phase transmission line supplies 100 kilowatts to a three-phase induction motor at 2300 volts line potential at 0.8 power factor (lagging current). A three-phase synchronous motor of 25 kilovolt-amperes capacity, connected in parallel with the induction motor, takes 15 kilowatts from the line. What is the best power factor that may be obtained for the combined load?

Ans. 0.902.

196. A factory takes 500 kilowatts, three-phase, at 0.8 power factor (lagging current), 8 hours each day, 300 days per year, at 2.1 cents per kilowatthour. The power company offers to reduce the rate if the power factor is increased to 0.9. The owner of the factory may purchase a synchronous motor for \$13.50 per kilovolt-ampere (installed) and the interest, depreciation, and taxes on this investment will be 12 per cent. When operated at no load with its excitation adjusted to make the power factor of the resultant load 0.9 (lagging current) the synchronous motor will take 20 kilowatts from the line. Neglecting the cost of the synchronous motor excitation, what is the least reduction in rate that would confirm the installation of the synchronous motor?

Ans. Reduce to less than 2 cents per kilowatthour.

197. A three-phase, 200-kilovolt-ampere synchronous motor is connected in parallel with a balanced three-phase inductive load to a 600-volt, three-phase line. The synchronous motor takes 100 kilowatts at an unknown power factor, the inductive load takes 120 kilowatts at 0.8 power factor (lagging current), and the power factor of the combined load is unity. At what per cent of its capacity is the synchronous motor operating?

Ans. 67.2 per cent.

198. The power factor of a three-phase load of 400 kilowatts at 0.85 power factor (lagging current) and 2300-volt line potential is to be improved by connecting a three-phase synchronous motor of 100-kilovolt-amperes capacity in parallel with it. The armature of the synchronous motor is Y wound and has a resistance of 2.7 ohms per phase. The rotational loss of the synchronous motor is 5 kilowatts and may be assumed constant. What is the best power factor that may be obtained in the combined load if the output of the synchronous motor is zero?

Ans. 0.94.

199. A factory takes 300 kilowatts from a three-phase transmission line at 0.85 power factor (lagging current). It is proposed to install in the factory a three-phase synchronous motor to be operated at no load and with its excitation adjusted to make the power factor of the resultant load 0.95 (lagging current). If the alternating-current power input to the synchronous motor at no load is 25 kilowatts, determine its capacity in kilovolt-amperes.

Ans. 82.8 kilovolt-amperes.

200. A Δ-connected, three-phase synchronous motor is operated at a line potential of 2300 volts with an armature phase current of 25 amperes at 0.8 power factor (lagging current). Determine the required percentage increase in the field flux to cause the synchronous motor to operate under the same load and armature current but at 0.8 power factor (leading current). The phase resistance and inductive reactance are each 4 ohms.

Ans. 5.82 per cent.

201. A three-phase 60-cycle generator supplies 100 kilowatts to a three-phase transmission line at 2300 volts line potential and 0.85 power factor (lagging current). Determine the capacitance in microfarads of each of three condensers connected in Y between the line wires at the generator which will make the power factor at the generator unity.

Ans. 31.2 microfarads.

202. A synchronous generator delivers power over a three-phase transmission line to a synchronous motor which drives a centrifugal pump. The synchronous generator is Y wound, has a phase resistance of 3 ohms, and a total rotational loss of 25 kilowatts. The transmission line has a resistance of 2 ohms per conductor. The synchronous motor is Δ wound, has a phase resistance of 6 ohms, and a total rotational loss of 20 kilowatts. When the power delivered to the centrifugal pump is 700 horsepower the line current is 50 amperes. Determine the horsepower output of the turbine driving the synchronous generator.

Ans. 830 horsepower.

Chapter XII

203. A single-phase synchronous converter is connected between a grounded 115-volt direct-current line and an alternating-

current radio receiver as shown in Fig. 269. An alternating-current voltmeter is connected between one of the alternating-current lines and the ground. Neglecting all impedance drops in

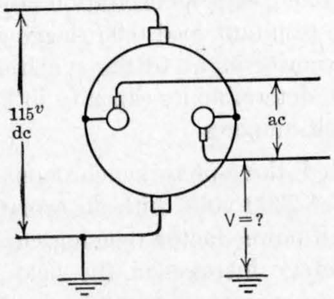


Fig. 269

the synchronous converter what will the voltmeter read? The wave form on the alternating-current side of the converter is to be assumed sinusoidal.

Ans. 70.3 volts.

Chapter XIV

204. A 10-kilowatt, 20-to-1 transformer takes 178 watts when the primary potential is 70 volts, the primary current is 4.5 amperes, and the secondary winding is short-circuited. Determine (a) the composite (or equivalent) resistance and (b) the composite (or equivalent) reactance of the transformer, each on the secondary side.

Ans. (a) 0.0219 ohm and (b) 0.0321 ohm.

205. What emf must be impressed upon the primary winding of the transformer described in Problem 204 when the secondary delivers 8 kilowatts at 115 volts terminal potential and 0.85 power factor (lagging current)?

Ans. 2360 volts.

206. The transformer described in Problem 204 takes 122 watts when the primary potential is 2360 volts and the secondary is open-circuited. Determine the efficiency of the transformer when the secondary delivers 8 kilowatts at 115 volts terminal potential and 0.85 power factor (lagging current)?

Ans. 96.7 per cent.

207. A 10-to-1 (primary to secondary) transformer has a secondary composite resistance of 0.02 ohm and a secondary composite reactance of 0.03 ohm. When delivering 30 kilowatts at 0.8 power factor (lagging current) the secondary terminal potential is 230 volts. Determine the per cent rise of the secondary potential when the above load is disconnected. The primary potential is assumed constant.

Ans. 2.4 per cent.

208. A transformer having a core loss of 1000 watts operates at an efficiency of 98 per cent when its output is 100 kilowatts. Assuming that its core loss, secondary terminal potential and load power factor remain constant determine the efficiency of the transformer when its output is 40 kilowatts.

Ans. 97.2 per cent.

209. A 6600-volt, three-phase transmission line supplies power to a three-phase synchronous converter through three single-phase transformers. The transformer primaries are connected in Y and the secondaries in Δ. Neglecting the impedances of the transformers and the converter what must be the ratio of transformation of each single-phase transformer to give a potential of 500 volts on the direct-current side of the converter?

Ans. 12.45.

210. Power is supplied from a three-phase transmission line to a three-phase induction motor through three single-phase transformers. The ratio of transformation (primary to secondary) of each transformer is 3.3. The secondary composite resistance of each transformer is 0.4 ohm and the secondary composite reactance of each transformer is 0.6 ohm. The primary windings of the three transformers are connected in Y and the secondary windings in Δ. Determine the required line potential of the transmission line when the input to the induction motor is 500 kilowatts at 2300 volts terminal potential and 0.8 power factor (lagging current).

Ans. 13,500 volts.

211. When the secondary output of a transformer is 50 kilowatts the primary input is 53 kilowatts at 2300 volts terminal potential and 0.8 power factor (lagging current). When the secondary

output is zero the primary input is 1 kilowatt at 2300 volts terminal potential. Determine the composite resistance of the transformer on the primary side.

Ans. 2.41 ohms.

212. The input to a transformer of 10 kilovolt-amperes rated capacity is 200 watts at no load and 5250 watts at half load (unity power factor). Determine the input at full load with the same power factor as at half load.

Ans. 10.4 kilowatts.

213. A three-phase transformer delivers a load of 100 kilowatts at 2300 volts line potential and 0.85 power factor to a three-phase induction motor. The primary windings are connected in Y and the secondary windings in Δ. The composite resistance and reactance of the transformer per phase on the secondary side are 2.0 ohms and 6.0 ohms respectively. Determine the power factor on the primary side (neglecting the core loss).

Ans. 0.835.

214. Three single-phase transformers are connected (Y–Y) between a three-phase transmission line and a three-phase induction motor. Each transformer has a secondary composite resistance of 0.1 ohm. With the secondary load disconnected the total power input to the three transformers is 12 kilowatts. Determine the total power input to the three transformers when the induction motor takes 400 kilowatts at 2300 volts terminal potential and 0.8 power factor.

Ans. 416.7 kilowatts.

215. Power is supplied from a three-phase transmission line through two V-connected transformers to a three-phase induction motor which takes 250 kilowatts at 0.85 power factor. Determine the required kilovolt-ampere capacity of each transformer.

Ans. 170 kilovolt-amperes.

Chapter XV

216. A 15-horsepower, 60-cycle, three-phase induction motor operates at full load at a speed of 1125 rpm. Determine (**a**) the number of phase sets in the stator winding, (**b**) the slip of the rotor at full load, and (**c**) the frequency of the rotor current at full load.

Ans. (**a**) 3, (**b**) 6.25 per cent, and (**c**) 3.75 cycles per second.

217. A three-phase, 60-cycle, induction motor having three phase sets develops a torque of 80 pound-feet at 6 per cent slip. The input to the motor is 16 kilowatts at 230 volts and a line current of 50 amperes. Determine (**a**) the speed, (**b**) the power factor, (**c**) the output, and (**d**) the efficiency of the motor.

Ans. (**a**) 1128 rpm, (**b**) 0.803, (**c**) 17.2 horsepower, and (**d**) 80 per cent.

Chapter XVI

218. The line current of a 5-horsepower, 115-volt, 25-cycle, alternating-current series commutator motor is 48 amperes at full load. The resistance of the armature and compensating winding combined is 0.1 ohm and the resistance of the field winding is 0.054 ohm. With the armature at rest the potential across the armature and compensating winding combined with an armature current of 48 amperes (25 cycles alternating current) is 13.1 volts. The potential between the terminals of the field winding with the same current is 52.1 volts. With the motor operating at full load at 115 volts terminal potential determine (**a**) the power factor of the motor, (**b**) the effective emf generated in the armature, (**c**) the rotational loss of the motor, and (**d**) the efficiency.

Ans. (**a**) 0.83, (**b**) 88.1 volts, (**c**) 495 watts, and (**d**) 81.3 per cent.

INDEX

INDEX